CHAPTER 7. FALSEWORK FOUNDATIONS

Section 7-1 Introduction

This chapter discusses the methods and procedures used by the Division of Structures to evaluate the adequacy of falsework pad and pile foundations. Also included is a brief discussion of other foundation systems occasionally encountered on bridge projects in California.

To an extent, the Division's procedures are approximations, having been developed from a subjective evaluation of the actual manner in which falsework pads and piles react when loads are applied. Although empirical in some cases, the procedures give results that are acceptable in the light of falsework requirements. To ensure uniformity, the Division's procedures are to be followed by bridge field personnel in all cases when reviewing the contractor's falsework design for structural adequacy and compliance with contract requirements.

From an administrative standpoint, the elements of the falsework system comprising the foundation differ from other elements of the system in one important aspect. The specifications permit the contractor to place falsework pads and drive falsework piles before the falsework design has been reviewed and the drawings approved. Division policy requires pad placement and pile driving to be inspected, to the extent necessary to ensure adequate foundation support, at the time the work is done. Any inconsistencies and differences between the falsework drawings and the work being performed in the field should be brought to the contractor's attention immediately.

Section 7-2 Timber Pads

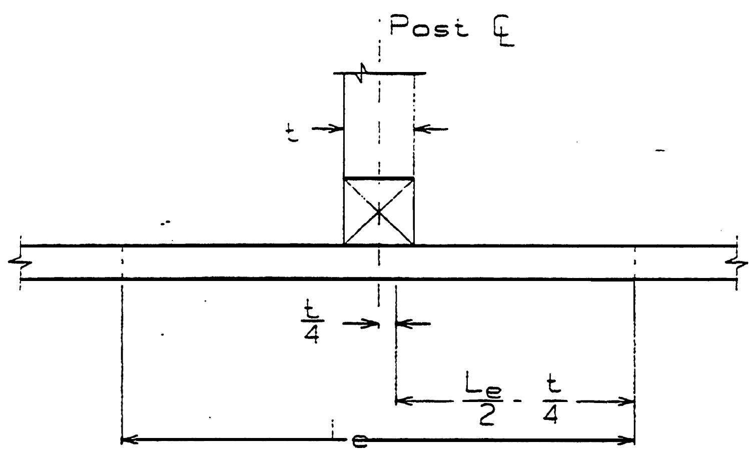
7-2. 0l Genera1

Falsework posts may be supported by individual pads, which may be square or rectangular, or several posts may be supported by a continuous pad. Additionally, a falsework pad may consist of a single member or of several members set side-by-side.

Corbels are short beams which are used to distribute the post load across the top of the individual pads in a multiple pad system. In a typical timber system the corbel will be a timber member of the same dimensions as the post it supports; however, steel wide-flange beams are often used as corbels when the post load is relatively high or in any case where steel posts or pipe columns ace used to carry the vertical load. Additionally, when the vertical design load is very high, as is often the case for a falsework bent adjacent to a wide traffic opening, it is often necessary to use two or more closely spaced corbels to adequately distribute the load over the falsework pad.

As a general design procedure, a falsework pad may be viewed as a cantilever beam extending from the face of the post or corbel. With the beam loaded uniformly with the soil pressure, bending and shear stresses may be calculated. Keep in mind, however, that this approach will not give exact values because the assumed uniform load distribution does not occur in actual practice.

To facilitate analysis of timber pad systems, the Division of. Structures has developed an empirical procedure which provides sufficient pad rigidity to assure a reasonably uniform load distribution. The Division's procedure is explained in the following sections, and illustrated in several example problems in Appendix D.



Formula for F_b = 1500 psi (pad thickness 8 inches or less)

$$L_e = \frac{1}{6}\left[\left(\frac{3t + 36S/P}{12}\right) + \sqrt{\left(\frac{3t + 36S/P}{12}\right)^2 - \frac{t^2}{16}}\right]$$

Formula for F_b = 1800 psi (pad thickness greater than 8 inches)

$$L_e = \frac{1}{6}\left[\left(\frac{3t + 43.202S/P}{12}\right) + \sqrt{\left(\frac{3t + 43.202S/P}{12}\right)^2 - \frac{t^2}{16}}\right]$$

In the formulas, L_e is the theoretical effective length of the pad in feet, t is the post width in inches, S is the pad section modulus in inches cubed, and P is the post load in kips.

FIGURE 7-l

7-2.02 Definitions

The term "theoretical effective length" means the maximum length over which a falsework pad is capable of distributing the post load uniformly, all other factors being equal.

The term "limiting length" means the length over which a specific falsework pad will actually distribute the post load uniformly at the post location under consideration.

7-2.03 Analysis of Continuous Pad Systems

In a continuous pad system where the posts are uniformly spaced, the theoretical effective length of the pad is equal to the post width plus twice the length of a cantilever extending from the face of the post or corbel a distance such that the calculated bending stress in the pad equals the allowable stress.

Figure 7-1 shows the formulas that are used to calculate the theoretical effective length at an interior post when the post spacing is uniform along the pad. Note that the theoretical effective length is measured along the pad in the direction of the wood grain, the cantilever length is measured from a point midway between the center and edge of the falsework post, and the effective length formulas are derived by applying the soil pressure load uniformly.

The two formulas shown in Figure 7-l are derived from quadratic equations, and their use requires a cumbersome calculation. To expedite the falsework design review, the Division has developed a simplified formula that may be used for the symmetrical loading condition that occurs when the post spacing is uniform. The simplified formula gives results that are accurate within one percent for the range of post loads and member sizes commonly used for falsework construction in California. For descriptive purposes, the simplified formula is designated the "SYM" formula. The SYM formula is:

$$L_{SYM} = t/12 + F_bS/1500P$$

where L_{SYM} is the theoretical effective length in feet; t is the width of the post or corbel in inches; F_b is the allowable bending stress in psi; S is the pad section modulus in inches cubed; and P is the post load in kips.

When the allowable bending stress value is substituted for F_b, the formula reduces to:

$$L_{SYM} = t/12 + S/P \quad \text{(when } F_b = 1500 \text{ psi)}$$

$$L_{SYM} = t/12 + (1.2)(S/P) \quad \text{(when } F_b = 1800 \text{ psi)}$$

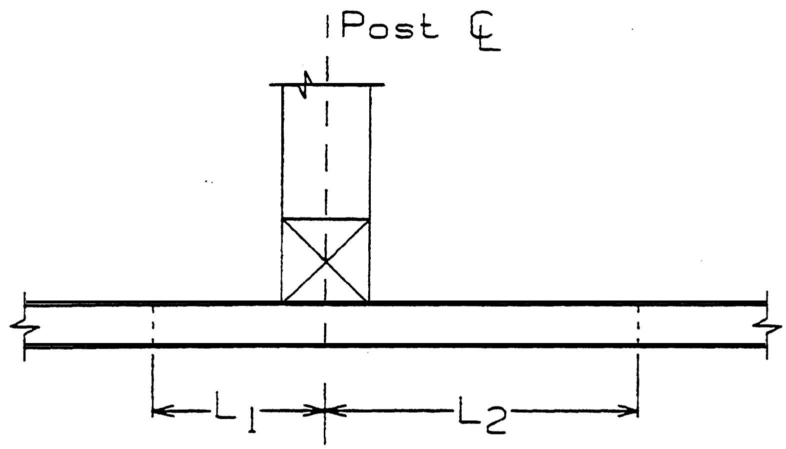


FIGURE 7-2

When the post spacing is not uniform, the pad is asymmetrical for analysis. For the asymmetrical condition, the limiting length of the pad on one side of a post will not equal the limiting length on the opposite side, and the two respective lengths must be determined independently. Furthermore, the calculations are complicated by the fact that it has not been possible to develop a simplified formula for the asymmetrical loading condition.

Refer to the asymmetrical load shown in Figure 7-2 and note the following:

L_1 is the limiting length on the short side, in feet.

> L_2 may not exceed the smaller of (1) one-half of the post spacing on the short side, or (2) one-half of the length determined by the SYM formula.

L_2 is the limiting length on the long side, if feet.

> L_2 may not exceed the smaller of (1) one-half of the post spacing on the long side, or (2) the length given by the long side effective length formula for the asymmetrical loading condition. For identification, this formula is designated the "ASYM" formula, The ASYM formula is:

$$L_{ASYM} = \frac{1}{2}\left(\frac{t}{24} + \frac{SF_b}{6000P}\right) + \sqrt{\frac{SF_bL_1}{6000P} - \frac{(t/12)^2}{16} + \left[\frac{1}{2}\left(\frac{t}{24} + \frac{SF_b}{6000P}\right)\right]^2}$$

It is important to note that the length given by both the SYM and the ASYM formulas is the pad length at which the actual bending stress i&the pad equals the allowable bending stress. Since the formulas are based on bending, it is not necessary to calculate the bending stress when evaluating system adequacy because, for a given post load, any pad length less than the length given by the formulas will produce a bending stress that is less than the allowable stress.

For the asymmetrical loading condition, pad bearing length, soil pressure and the horizontal shear in the pad on the long side are given by the following formulas:

$$\text{Bearing length (feet)} = L_1 + L_2$$

$$\text{Soil pressure (psf)} = \frac{(1000)(P)}{(L_1 + L_2)(b/12)}$$

$$\text{Horiz. shear (psi)} = \frac{3}{2} \times \frac{(1000)(P)}{L_1 + L_2} \times \frac{L_2 - t/24 - d/12}{(b)(d)}$$

In the preceding formulas, P is the post load in kips; S is the pad section modulus in inches cubed; F_b is the allowable bending stress; t is the width of the post or corbel in inches; b is the pad width in inches; and d is the pad thickness in inches.

7-2.03A Pad Analysis at Interior Posts

Figure 7-3 shows a falsework bent where the post spacing is uniform along a continuous pad and the post load is distributed across the pad by a single corbel. In the figure, "PS" is the post spacing (and also the corbel spacing) and "L_e" is the theoretical effective length given by the SYM formula.

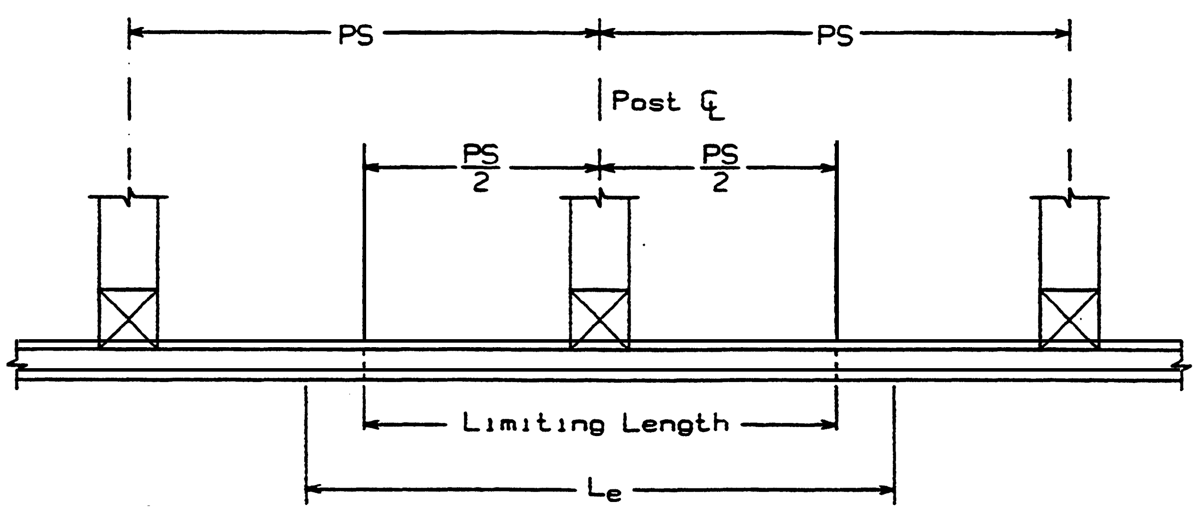


FIGURE 7-3

When the post spacing is uniform, the bearing length is symmetrical. System adequacy is evaluated as follows:

1. For a given post, calculate the theoretical effective length of the pad using the SYM formula.

2. Compare the length from step 1 and the post spacing. The shorter of these two lengths is the limiting length, or the length to be used in the analysis.

   The bearing length in the Figure 7-3 example is determined by post spacing. In general, this will be the case for falsework bents on California projects, However, when relatively light members are used as pads, post spacing may not be the determining factor; therefore, the step 2 comparison must be made in all cases.

3. Using the post spacing (or the effective length if the effective length governs) calculate the soil pressure.

4. If the soil pressure does not exceed the allowable soil bearing value, calculate the stress due to horizontal shear. For this calculation, consider the pad as a continuous beam loaded uniformly with the soil pressure over a length equal to the bearing length determined by the step 2 comparison, and calculate the stress at a distance "d" from the face of the post or corbel where "d" is the pad thickness.[1]

When the post spacing is not uniform, the contribution to system adequacy made by the pad on one side of a post must be determined independently of the contribution made by the pad on the opposite side.

Refer to the system shown in Figure 7-4, System adequacy is evaluated as follows:

1. Use the SYM formula to calculate the theoretical effective length of the pad at the post under consideration.

2. Compare one-half of the length from step 1 and one-half of the post spacing to the left of the post. The shorter of these two lengths is the limiting length (the length that actually contributes to system adequacy) on the left side.

   In this example the left side comparison is made first because, for the post configuration shown in Figure 7-4, the post spacing to the left of the post is less than the spacing to the right:

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[1] See Chapter 4, Section 4-2.05, Horizontal Shear, for a general discussion of horizontal shear in timber beams.

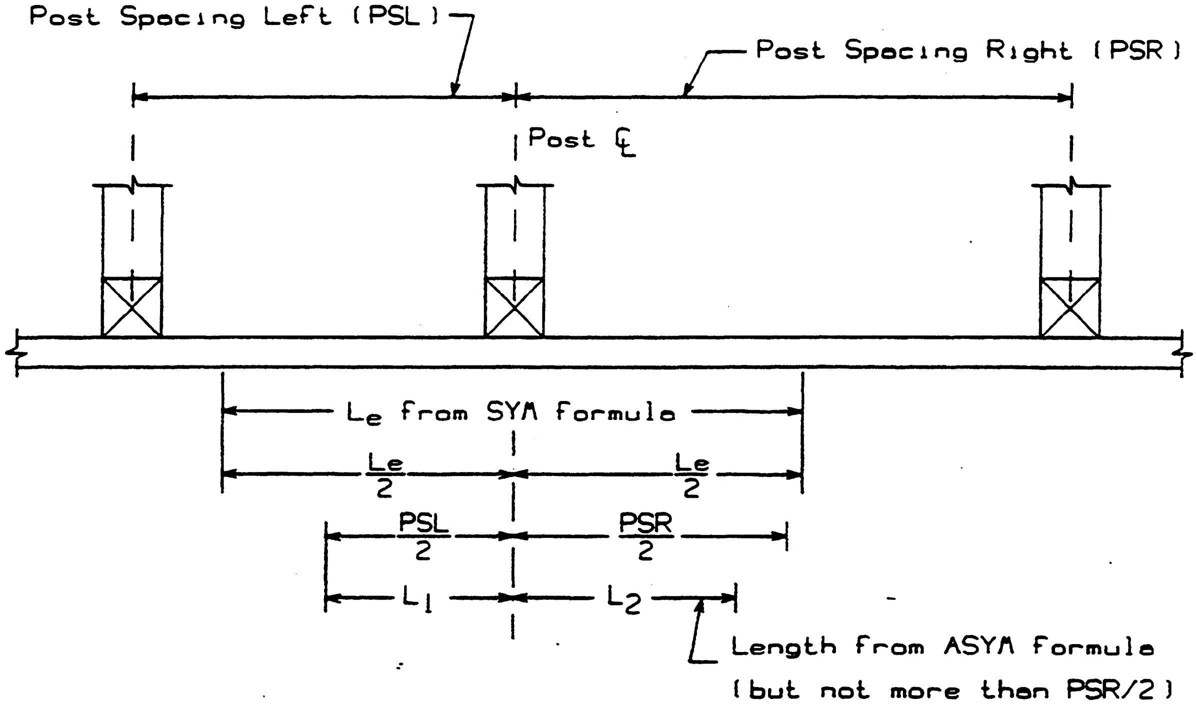

FIGURE 7-4

3 . If the limiting length on the short side of the post is one-half of the theoretical effective length as determined by the SYM formula, the bearing length is symmetrical for analysis. (Note that this is not the case in Figure 7-4.)

If the bearing length is symmetrical, calculate the soil pressure and the stress due to horizontal shear following the procedure explained above for the symmetrical analysis.

4 . If the limiting length on the short side **(L_1)** is one-half of the post spacing, as shown in the Figure 7-4 example, the bearing length is asymmetrical.

For the asymmetrical analysis, calculate a new effective length on the long side using the ASYM formula. (The ASYM formula is shown on Page 7-4)

5 . Compare the long side effective length from step 4 and one-half of the post spacing on the long side. The shorter of these two lengths is the limiting length **(L_2)** the long side. (The long side is the right side in Figure 7-4.)

6 . The sum of the limiting lengths found in steps 2 and 5 is the bearing length at the post under consideration.

3. Using the bearing length from step 6, calculate the soil pressure. If the soil pressure does not exceed the allowable soil bearing value, calculate the stress due to horizontal shear on the long side using the formula shown on Page 7-5.

7-2.03B Pad Analysis at Exterior Posts

For exterior posts, the contribution to system adequacy made by the length of pad on the outside of the post must be determined independently of the contribution made by the pad on the inside. [2]

Figure 7-5 shows the post configuration for an exterior post in a typical continuous pad system. System adequacy is evaluated as follows:

1. Use the SYM formula to calculate the theoretical effective length of the pad at the exterior post.

2 . Multiply the calculated length by a stiffness coefficient of 0.8 to obtain an adjusted effective length. (Note that this step is necessary because the pad length on the outside of an exterior post resists the applied loads in the same manner as an individual falsework pad. See the discussion in Section 7-2.04, Analysis of Individual Falsework Pads.)

3 . Determine the limiting length on the outside of the post by comparing one-half of the adjusted effective length and the distance from the center of the post to the end of the pad. The smaller of these two values is the limiting length (L_1) on the outside of the post.

4 . Determine a preliminary limiting length on the inside of the post by comparing one-half of the theoretical effective length calculated in step 1 and one-half of the distance (post spacing) to the first interior post. The smaller of these two values is the preliminary limiting length on the inside of the post.

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[2] For typica1 bent configurations and post spacing, the pad length on the inside of the post will be the long side for the analysis. Keep in mind, however, that the procedure for evaluating system adequacy as explained herein is also valid in any case where the long side length is on the outside.

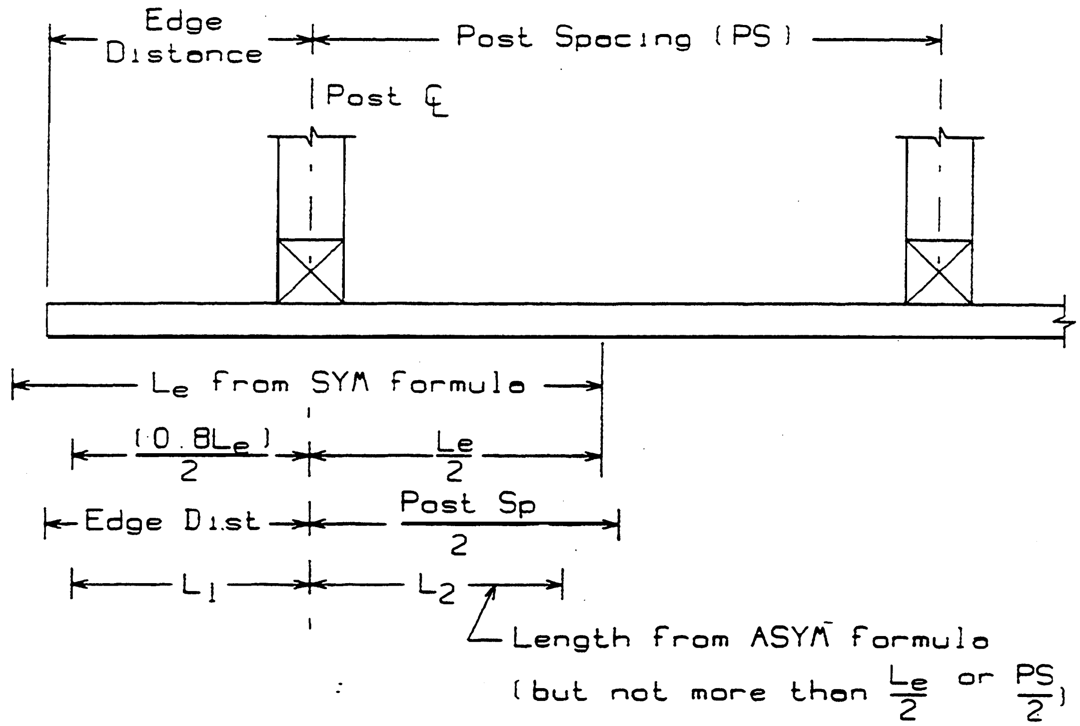

FIGURE 7-5

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5 .If the step 3 and step 4 limiting lengths are equal, the bearing length is symmetrical and pad adequacy may be evaluated using the procedure for uniformly spaced interior posts. (But note that this is unlikely to occur in actual practice.)

6 .If the step 3 and step 4 lengths are unequal, the bearing length is asymmetrical. For the asymmetrical loading it is necessary to calculate the effective length of the pad on the inside of the post (the long side) using the ASYM formula.

Compare the length obtained from the ASYM formula and the preliminary limiting length from step 4. The shorter of these two lengths is the limiting length **(L_2)** on the inside of the post.

7 . Add the limiting length on the outside and the limiting length on the inside to obtain the bearing length.

8 . Using the bearing length from step 7, calculate the. soil pressure and the stress due to horizontal shear in the pad on the long side using the formulas on Page 7-5.

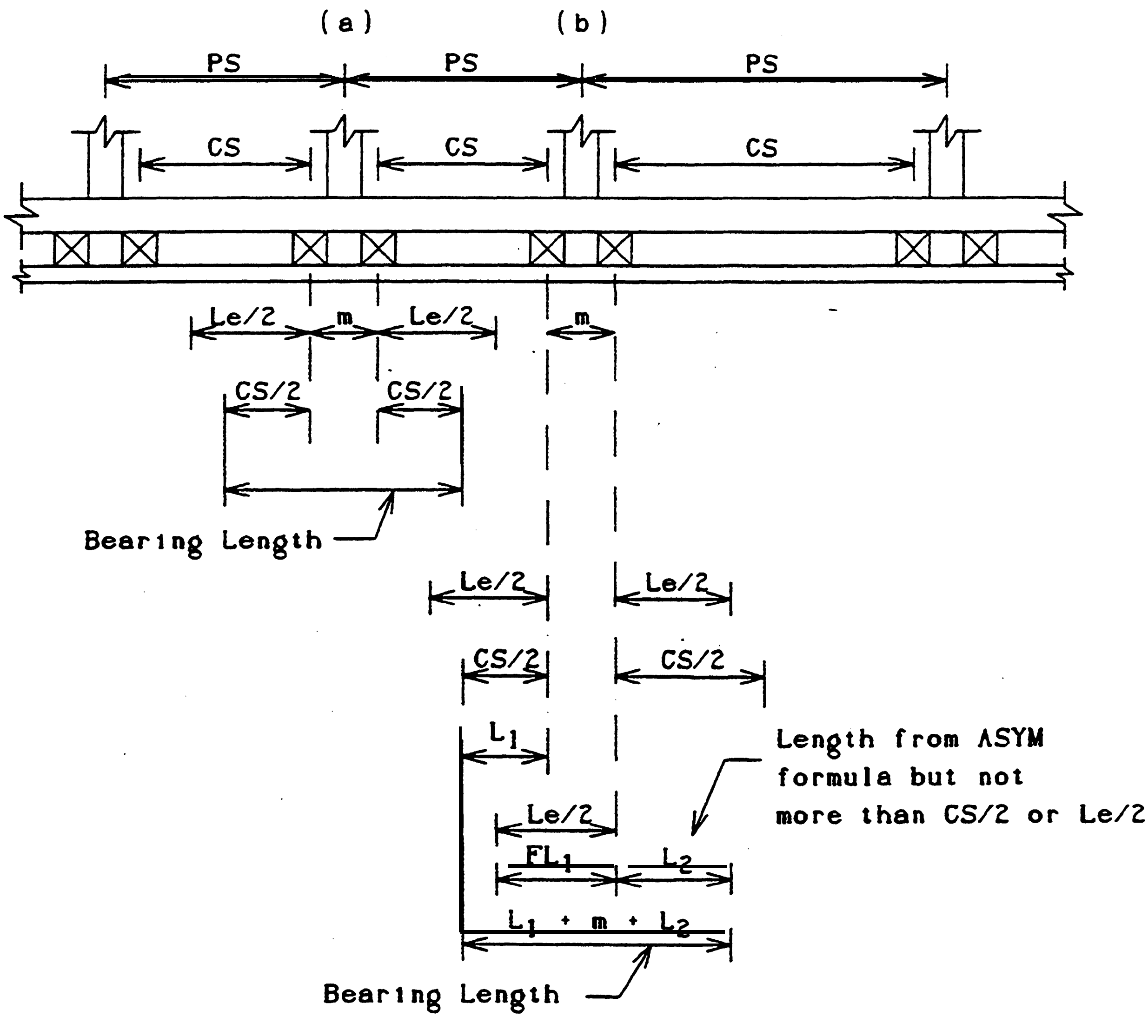
(a)
(b)
PS
PS
PS
CS
CS
CS
Le/2
m
Le/2
m
CS/2
CS/2
Bearing Length
Le/2
Le/2
CS/2
CS/2
L1
Length from ASYM formula but not more than CS/2 or Le/2
Le/2
FL1
L2
L1 + m + L2
Bearing Length

FIGURE 7-6

7-2.03C Multiple Corbel Systems

The term "post spacing" has been used in the preceding section to facilitate understanding of the Division's procedure for pad analysis in continuous pad systems. But as previously noted, when the falsework pad is made up of two or more individual members placed side-by-side, as is typically the case, corbel beams are used to distribute the post load uniformly across the top of the pad. As a design. concept, then, the limiting length determination actually involves consideration of the corbel spacing rather than the post spacing, even though in many cases the two distances are the same.

This distinction is not of any practical consequence when each post has its own individual corbel; however, when the vertical load is distributed to a continuous pad through a system of two or more closely spaced corbels, the procedure for evaluating pad adequacy for the asymmetrical loading condition as discussed in the preceding section gives limiting lengths that are shorter, and soil bearing values that are higher, than is actually the case. This circumstance occurs because, as the-corbel spacing approaches the corbel width, the pad distributes the total load as though it were actually imposed by a single corbel having a width along the pad of approximately the distance between the outside faces of the adjacent corbels.

In view of the manner in which falsework pads respond to loads applied by closely spaced corbels, the Division has developed an alternative procedure for evaluating pad adequacy in a multiple corbel system. The alternative procedure should be used when the clear distance between adjacent corbels is equal to or less than twice the thickness of the falsework pad.

7-2.03C(1) Multiple Corbel Analysis at Interior Posts

Figure 7-6 shows a typical multiple corbel system, When the post spacing is uniform, as is the case at post (a), bearing length is symmetrical and pad adequacy is evaluated as follows:

1 . Calculate the theoretical effective length of the falsework pad using the SYM formula. For this calculation, use the post load, not the load applied by the corbel.

   Note that it is necessary to use the post load because the pad responds to loads applied by a system of closely spaced corbels as though the loads were actually applied by a single corbel.

2 . Compare one-half of the length from step 1($L_c/2$) and one-half of the corbel spacing. (Corbel spacing is designated as "CS" in Figure 7-6.) The shorter of these two lengths is the limiting length on both sides of the system.

The limiting length at post (a) in Figure 7-6 is determined by the corbel spacing, and this is usually the case for falsework designs on California projects. However, if the pad is made up of relatively light members, corbel spacing may not be the determining factor; therefore, the step 2 comparison must be made in all cases.

3. Determine the bearing length. The bearing length is the sum of the limiting lengths on either side of the corbel system plus the distance between the corbel centerlines. (The distance between the corbel centerlines is designated as "m" in Figure 7-6.)

4. Calculate soil pressure and the stress due to horizontal shear.

Because of bearing length symmetry, the limiting lengths on each side of the system will be equal; consequently, the procedure may be simplified as follows:

1. Calculate the theoretical effective length of the pad using the SYM formula and the post load. Compare this length and the corbel spacing. The shorter of these two lengths plus the distance "m" is the bearing length.

2. Using the bearing length from step 1, calculate soil pressure and the stress due to horizontal shear.

When the system is asymmetrical, as is the case at post (b) in Figure 7-6, the procedure is as follows:

1. Calculate the theoretical effective length of the falsework pad using the SYM formula and the total post load.

2. Compare one-half of the length from step 1 and one-half of the corbel spacing on the short side of the system. The shorter of the two compared lengths is the limiting length on the short side. (In Figure 7-6, the short side is the left side and the limiting length is one-half of the corbel spacing to the left of the post.)

   If the limiting length on the short side is one-half of the theoretical effective length, the bearing length will be symmetrical for analysis. In such cases, pad adequacy may be evaluated by the procedure previously explained for the symmetrical loading condition. (As previously noted, however, this is not usually the case, and it is not the case in the Figure 7-6 example.)

3. If the limiting length on the short side is one-half of the corbel spacing, as is the case at post (b) in Figure 7-6, the bearing length is asymmetrical. For the asymmetrical condition it is necessary to calculate the effective pad

length on the long side using the ASYM formula and a fictitious limiting length on the short side. As shown in Figure 7-6, for descriptive purposes the fictitious limiting length is designated as FL_1.

FL_1 will be numerically equal to one-half of the effective length calculated in step 1 but not more than one-half of the corbel spacing on the short side plus the distance "m". (In the Figure 7-6 example FL_1 is equal to one-half of the effective length because this length is less than one-half of the corbel spacing on the short side plus "m".)

4. Calculate the theoretical effective length on the long side using the ASYM formula and FL_1 from step 3.

5. Compare one-half of the theoretical effective length from step 1, the long side effective length from step 4 and one-half of the corbel spacing on the long side. The shortest of these three lengths is the limiting length (L_2) on the long side. (In the Figure 7-6 example, L_2 is one-half of the theoretical effective length.)

6. Determine the bearing length. The bearing length is the sum of the short side limiting length from step 2, the long side limiting length from step 5, and the distance "m". See Figure 7-6.

7. Using the bearing length from step 6, calculate the soil pressure. If soil pressure does not exceed the allowable soil bearing value, calculate the stress due to horizontal shear in the long side of the pad.

The procedures described above for two corbel systems are also applicable when three (or more) corbels are used to distribute the vertical load. In such cases, the length "m" is the distance (measured centerline-to-centerline) between the two outermost corbels in the system.

In some cases the load from two (or more) posts will contribute to the total vertical load to be distributed through the corbel system. For this configuration, the total load applied to the system must be used to calculate the effective length of the pad.

<u>7-2.03C(2) Multiple Corbel Analysis at Exterior Posts</u>

Figure 7-7 shows a multiple corbel configuration at an exterior post. When the short side is on the outside of the post, as is the case in Figure 7-7, system adequacy is evaluated as follows:

1. Calculate the theoretical effective pad length-using the SYM formula and the post load.

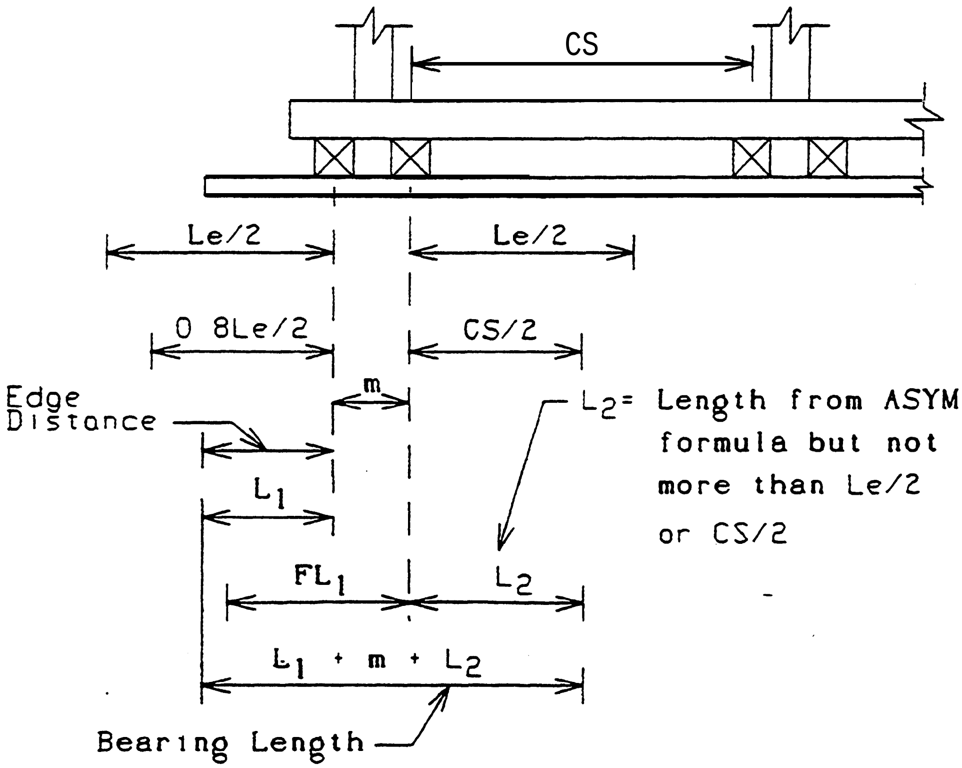

FIGURE 7-7

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2 . Multiply one-half of the length from step 1 by a stiffness coefficient of 0.8 to obtain. an adjusted effective length of pad on the outside of the exterior post. (This step is. necessary because the pad on the outside of an exterior post resists the applied loads in the same manner as an individual falsework pad. See Section 7-2.04, Analysis of Individual Falsework Pads.)

3 . Determine the limiting length on the outside of the post by comparing the adjusted effective length from step 2 and the distance from the center of the outside corbel to the end of the pad, The smaller of these lengths is the limiting length (L_1) on the outside of the exterior post system.

4 . Determine a preliminary limiting length on the inside of the post by comparing one-half of the theoretical effective length calculated in step 1 and one-half of the corbel spacing. The smaller of these lengths is the preliminary limiting length on the inside of the exterior-post.

5. If the step 3 and step 4 limiting lengths are equal, the bearing length is symmetrical and pad adequacy may be evaluated by the procedure for uniformly spaced interior posts explained in the preceding section.

6. If the step 3 and step 4 lengths are unequal, the bearing length is asymmetrical. For the asymmetrical condition it is necessary to calculate the effective pad length on the inside of the post (the long side) using the ASYM formula and a fictitious short side limiting length. (See FL_1 in Figure 7-7.)

   FL_1 will be numerically equal to one-half of the adjusted effective length calculated in step 2, but not more than the outside edge distance plus the distance "m". (In the Figure 7-7 example, FL_1 is the numerical equivalent of one-half of the adjusted effective length.)

7. Calculate the theoretical effective length on the long side using the ASYM formula and FL_1 from step 6.

8. Compare the long side effective length from step 7 and the preliminary limiting length from step 4. The shorter of these two lengths is the limiting length (L_2) on the inside of the post.

9. Determine the bearing length. The bearing length is the sum of the outside limiting length from step 3, the inside limiting length from step 8, and the distance "m". See Figure 7-7.

10. Using the bearing length from step 9, calculate the soil pressure. If soil pressure does not exceed the allowable soil bearing value, calculate the stress due to horizontal shear in the pad on the inside of the post,

The same general procedure applies when the short side is on the inside of an exterior post. For such cases the limiting lengths are determined as follows:

1. The limiting length on the inside of the post (L_1) is the shorter of one-half of the effective length calculated by the SYM formula or one-half of the inside corbel spacing.

2. The fictitious limiting length (FL_1) is one half-of the effective length calculated by the SYM formula, but not more than one-half of the corbel spacing plus "m".

3. The limiting length on the outside of the post is the length calculated by the ASYM formula but not more than the shorter of the edge distance or one-half of the effective length multiplied by the stiffness coefficient.

7-2.04 Analysis of Individual Falsework Pads

The SYM and ASYM formulas and the review procedures discussed in the preceding section were developed specifically for analysis of continuous pad systems. Because of the rigidity provided by beam continuity, continuous pads are stiffer members than individual pads of the same width and thickness; consequently, continuous pads have greater ability to distribute the post load uniformly, all other factors being equal.

Application of the Division's review procedure to individual pads requires an accommodation to account for the greater rigidity inherent in continuous pad systems. This is accomplished by multiplying the length given by the SYM and ASYM formulas by a stiffness coefficient of 0.8 to obtain an adjusted (shorter) length to use in the individual pad analysis. Use of the stiffness coefficient gives an effective length that reflects the load distribution actually achieved by an individual pad, and thus assures that the procedures used to evaluate the adequacy of continuous and individual falsework pads are compatible.

In other respects, the procedures used to evaluate individual pads are similar to those used in the analysis of continuous pads, as discussed in the following sections.

7-2.04A Analysis of Symmetrical Pads

Figure 7-8 shows an individual falsework pad where the bearing length is symmetrical about the post centerline. For the symmetrical loading, pad adequacy is verified as follows:

1. Calculate the theoretical effective length of the pad using the SYM formula.

2. Multiply the theoretical effective length by the stiffness coefficient of 0.8 to obtain an adjusted effective length.

   The adjusted effective length may not exceed the actual pad length. Therefore, if the adjusted effective length is greater than the actual length, use the actual length in the remaining calculations. (See Figure 7-8.)

3. Using the governing length (adjusted effective length or actual length) from step 2, calculate the soil pressure.

4. If the soil pressure does not exceed the allowable soil bearing value, calculate the stress due to horizontal shear. For this calculation, consider the pad as a beam loaded uniformly with the soil pressure over the length determined in step 2.

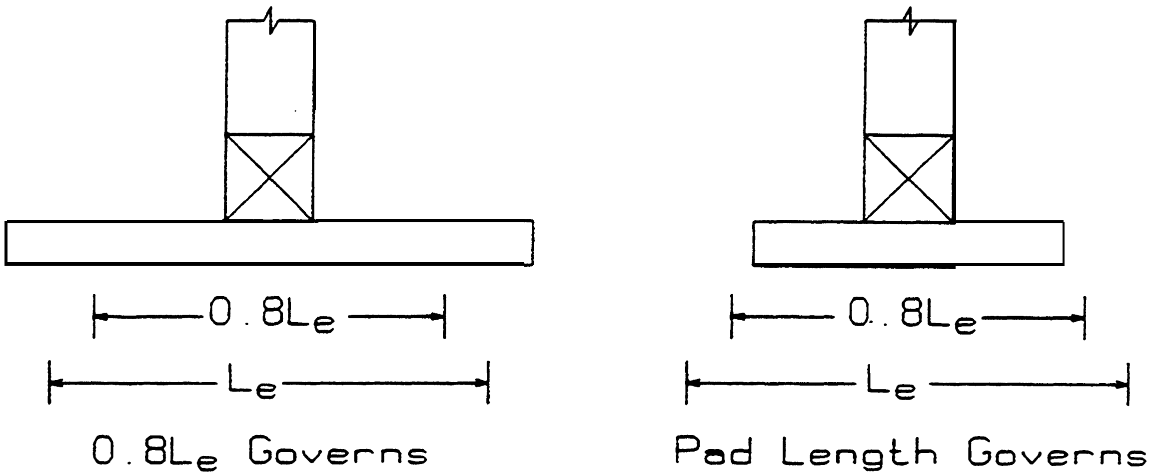

FIGURE 7-8

7-2.04B Analysis of Asymmetrical Pads

Refer to Figure 7-9 which shows a non-symmetrical loading. Pad adequacy is evaluated as follows:

1. Calculate the theoretical effective length using the SYM formula. Multiply the calculated value by the stiffness coefficient (0.8) to obtain the adjusted effective length.

2. Compare one-half of the adjusted effective length and the actual length of the pad cantilever on the short and long sides of the post. The shorter of the two compared lengths on each side of the post is the limiting length on that side. (See Figure 7-9)

3. If the limiting length on the both sides of the post is one-half of the adjusted effective length, the bearing length is symmetrical. In such cases system adequacy may be evaluated by the procedure described in steps 3 and 4 for symmetrically loaded pads.

4. When the limiting length on the short side is the pad length, as shown in the Figure 7-9 example, the bearing length is asymmetrical. For the asymmetrical loading condition, calcu1ate a new effective length on the long side using the ASYM formula.

5. Multiply the length given by the ASYM formula by the stiffness coefficient (0.8) to obtain the limiting length on the long side.

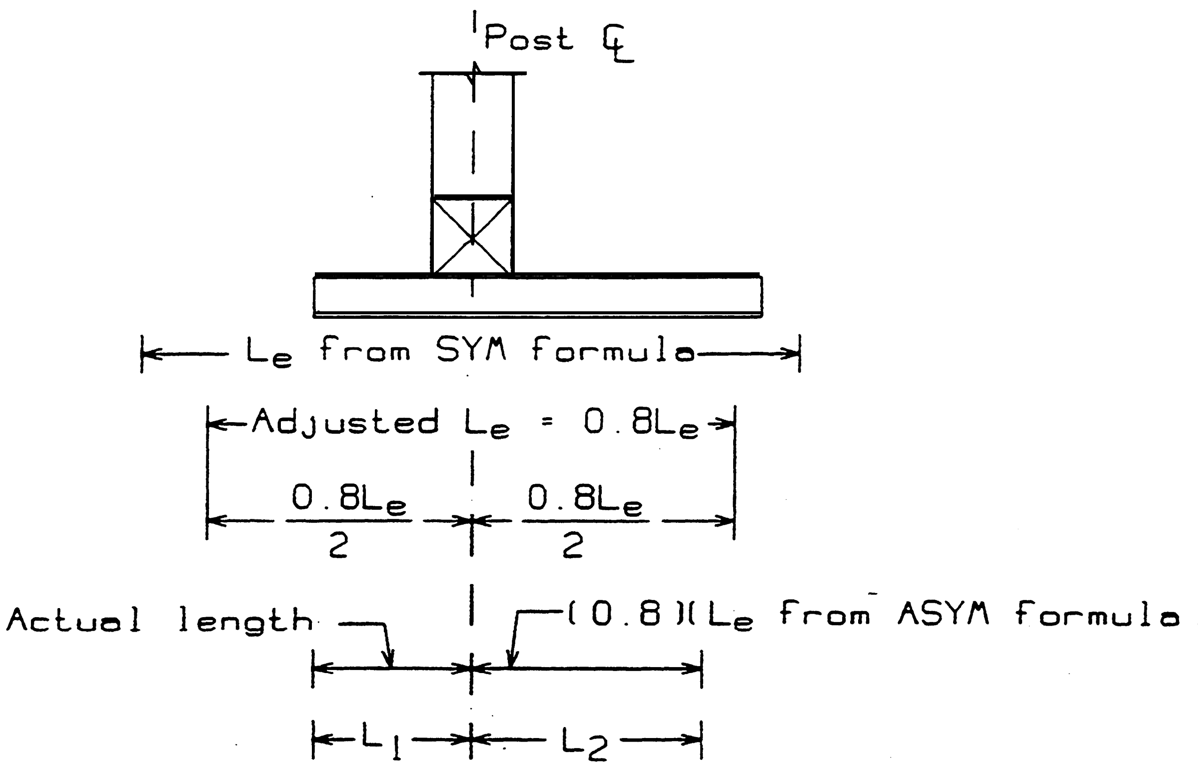

FIGURE 7-9

6. Add the short and long side limiting lengths **(L_1 and L_2)** to obtain the bearing length. (In figure 7-9 L_1 is the actual pad length and L_2 is the adjusted effective length from the ASYM formula.)

7 .Using the bearing length from step 7, calculate the soil pressure. If the soil pressure does not exceed the allowable soil bearing value, calculate the stress due to horizontal shear in the pad on the long side using the formulas on page 7-5.

   For some asymmetrical loading configurations, the adjusted ASYM length **(L_2)** will be <u>shorter</u> than the L_1 length, in which case the stress due to horizontal shear will be calculated on the L_1 side. (See Example Problem 1lB.)

<u>7-2.05 Joints and Joint Location in Continuous Pads</u>

To ensure the uniform load distribution assumed in the analysis, joints (that is, points of pad discontinuity) are not permitted within the limiting length of any continuous falsework pad, unless doubler pads or supplemental pads are provided.

If, because of the post spacing or other design consideration, joints must be located within the limiting length of a continuous pad, and if neither supplemental pads nor doubler pads are to be used, the interior posts adjacent to the joint must be viewed as exterior posts for analysis. If the falsework pad meets the exterior post criteria, the system is adequate at that location,

Joint location, because it directly affects the ability of a continuous pad to distribute the post load uniformly, is an important design consideration. Joint location must be planned in advance and shown on the falsework drawings, unless either doubler pads or one or more supplemental pads are to be used.

Any intended use of supplemental or doubler pads must be shown on the falsework drawings.

7-2.05A Supplemental Pads

To facilitate construction, some contractors intentionally over-design a continuous pad system by providing a greater overall pad width, and a correspondingly greater number of-individual pad members, than would be required by theoretical design considerations. The redundancy provided by the supplemental pads allows greater flexibility in joint location.

When supplemental pads are provided, joints may be located within the limiting length of a continuous pad system, subject to the following restrictions:

1. Joints in adjacent members must be staggered.

2. At any given joint location, the net width of the continuous pad system may not be less than would be required if supplemental pads were not used. (Net width is the width remaining after deducting the width of all pads having joints at the location under consideration.)

3. Joints in individual members comprising the net width of the continuous pad system, as defined above, may not be located closer to the joint in the supplemental pad than the limiting length at that joint location.

Since supplemental pads are not considered in the analysis, they must be clearly identified as such on the falsework drawings.

7-2.05B Doubler Pads

A doubler pad, which is a second pad placed on top of the main pad, may be used to carry the post load across a joint located within the limiting length of the main pad.

A doubler pad may be an individual pad at a given post location or a continuous pad placed between two or more posts. To

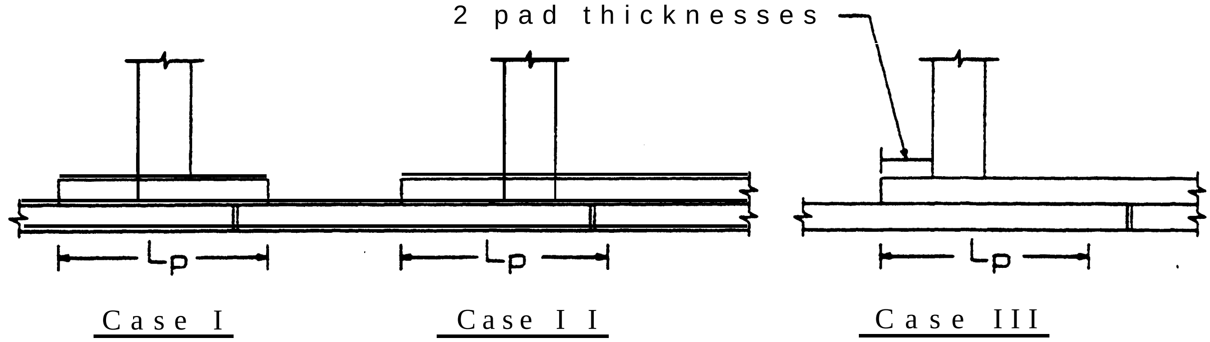

FIGURE 7-10

maintain the integrity of a continuous pad system, doubler pads must be of the same width and thickness as the main-pad, and they must be installed as provided in the following paragraphs,

Refer to Figure 7-10 and note that length **"L_p"** is the adjusted effective length of a symmetrically loaded phantom pad designed in accordance with Section 7-2.04. Analysis of Individual Pads. Use of doubler pads must conform to the following criteria:

1 . If a joint in the main continuous pad falls within the zone established by length L_p, either an individual doubler pad or a continuous doubler pad may be used. If an individual pad is used, it must be long enough to completely cover the L_p zone. (See Case I in Figure 7-10.) If the doubler pad is continuous, it must extend past the adjacent post to the edge of the L_p zone. (Case II in Figure 7-10.)

2 . If a joint in the main continuous pad falls beyond the L_p zone but within the limiting length of the main pad, a continuous doubler pad must be used, and it must extend past the posts on either side of the joint at least two pad thicknesses. (Case III in Figure 7-10.)

7-2 .06 Corbels

Corbels are short beams used to distribute the post load across the top of the individual pads in a multiple pad system.

When a corbel is used, Division of Structures policy requires that it extend across the full width of the pad even though extension of the corbel to the outside of the pad may not be required by theoretical design considerations.

The Division's procedure for evaluating corbel adequacy is based on the following assumptions:

1. The post load is applied symmetrically and is uniformly distributed across the full width of the pad.

   The assumed symmetry may not be valid in the case of a continuous pad system where one or more supplemental pads are used to facilitate joint location. However, assuming a symmetrical load distribution will give a conservative result when supplemental pads are used, and the assumption greatly simplifies the calculation.

2. When resisting the load applied by the pad, the corbel acts like a cantilever beam.

3. For timber corbels, the point of fixity of the cantilever beam (and the point of maximum bending moment) is located mid-way between the centerline and outside face of the post.

4. For steel beam corbels, the point of fixity (and the point of maximum moment) is located in a vertical plane at the outside face of the post.

5. If a round post is used, the post width to be used in the analysis is the length of the side of an equivalent area square post.

7-2.06A Timber Corbels

Figure 7-11 shows a typical timber corbel system where the post is rectangular. System adequacy is evaluated as follows:

1. Calculate the perpendicular-to-grain bearing stress at the interface between post and corbel.

   If the calculated stress exceeds the allowable stress, the system must be redesigned to reduce the post load or the load must be distributed over a larger bearing area by means of a steel plate. If a steel plate is used, the analysis is based on the assumption that the post width is numerically equal to the length of the steel plate.

2. Calculate the vertical shear at a distance from the face of the post equal to the depth of the corbel. Calculate the horizontal shearing stress at this location.

3. If horizontal shearing stress does not exceed the allowable stress, calculate the bending moment and the bending stress. The system is adequate if the calculated bending stress does not exceed the allowable stress.

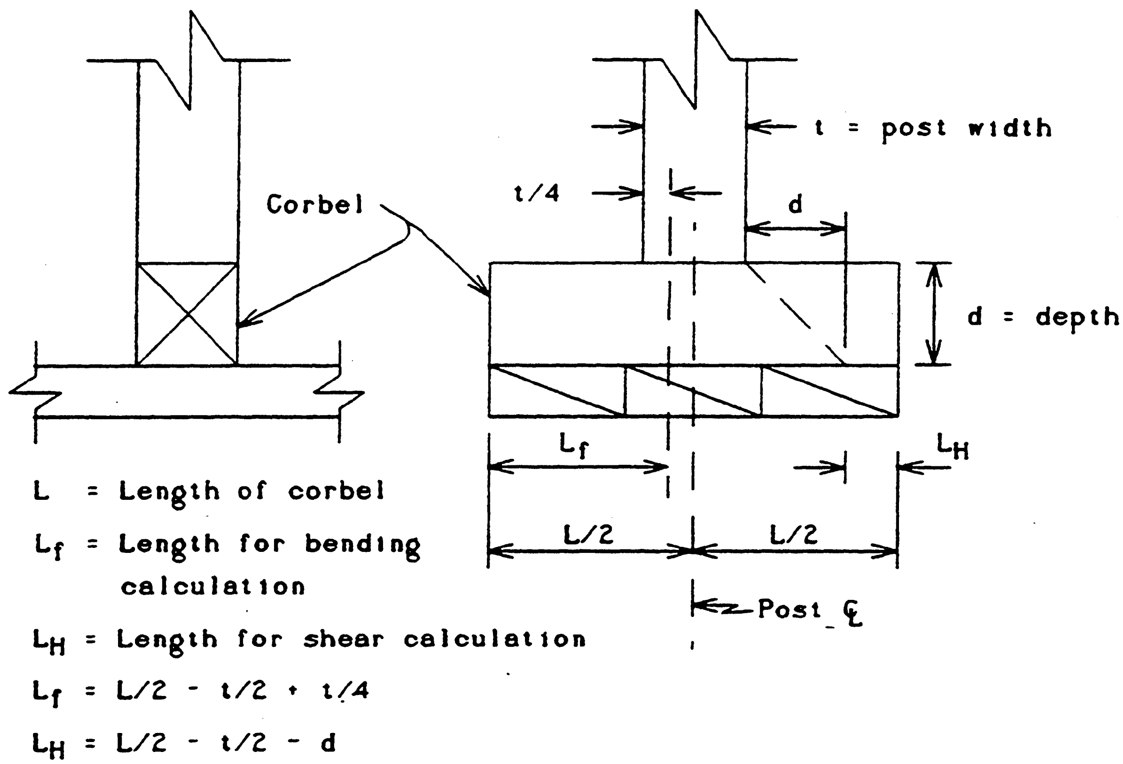

FIGURE 7-11

7-2.06B Steel Corbels

For steel beam corbels the procedure is as follows:

1. Calculate the web crippling stress under the post using the total post load.

   If the calculated stress exceeds the allowable, the length of bearing must be increased or the beam web stiffened.

2. Calculate the shear stress on the beam web using one-half of the total post load.

3. Calculate the bending moment and the bending stress. (For steel beam corbels, the cantilever length is measured from the face of the post.)

4. Calculate the perpendicular-to-grain bearing stress at the interface between corbel and pad.

Section 7-3 Pile Foundations

7-3.01 Genera1

In general, pile foundations will be required whenever site conditions preclude the use of timber pads or concrete footings, Typically, piles are used to support falsework for structures. over water, for falsework such as heavy duty shoring where leg loads are high and/or where differential settlement must be prevented, and for any type of falsework where a conventional foundation is not feasible because of poor soil conditions.

In most cases timber piles will provide the most economical pile foundation. However, the design load on timber piles is limited to 45 tons; consequently, steel piles may be more economical when large loads are to be carried. Regardless of other considera-tions, steel piles may be the better choice at any location where difficult driving conditions are anticipated.

Driven piles may be cut off and capped near the-ground line, in which case the superstructure load will be carried by braced bents erected on top of the pile cap. In this configuration the piles will be supported throughout their length; therefore, they will be subjected to axial loading only. Unless driven by a drop hammer, such piles may be considered as capable of carrying a load equal to the bearing value given by the ENR formula, but not more than 45 tons for timber piles.

If a drop hammer is used, the ENR bearing value should be divided by a safety factor of 1.5 to obtain the allowable pile capacity. Also, unless the hammer weight is clearly evident, the contractor should be required to substantiatethe weight used in the bearing calculations.

Occasionally, site conditions will dictate the use of pile bents extending above the ground surface. Such bents may be unbraced, partly braced or fully braced depending on site conditions. Most pile bent designs will use timber piles; however, steel piles are also used when warranted by site or design considerations.

7-3.02 Capacity of Timber Piles in Pile Bents

The load-carrying capacity of timber piles in a pile bent is a function of many variable factors. For example, the type of soil, the depth at which the piles are fixed in the ground, the deviation of the piles from their theoretical position, and the contribution to system stability provided by diagonal bracing all affect the ability of timber pile bents to resist the applied loads, and all must be considered in the analysis.

Furthermore, the procedures used to evaluate pile capacity differ from those used in the analysis of other components of the falsework system because the pile analysis must consider the combined effect of vertical loads, horizontal loads and eccentric loading conditions to ensure that allowable stresses are not exceeded.

The factors that influence pile capacity are discussed in detail in the following sections.

7-3.02A Required Pile Penetration

The Division's procedure for analysis of timber pile bents is valid only if the piles penetrate the subsurface soils to the depth necessary to develop a point of contraflexure in the embedded pile. (In a driven pile, the point of contraflexure, or the point of pile fixity as it is called in the pile analysis, is the location below the ground surface where the pile shaft may be considered as "fixed" against rotation when it is subjected to a bending moment.)

Other factors being equal, the depth of embedment needed to develop pile fixity is a function of soil type. Obviously, soft soils require a deeper-penetration than firm soils, but determining the actual penetration required is a matter of engineering judgment.

The Division of Structures uses the ratio of the depth of pile penetration to the height of the pile above ground (expressed as D/H) as the criterion to ascertain whether a given pile is embedded deeply enough to develop a point of fixity. For the stress analysis, piles are considered fixed at the predicted depth below the ground surface when the D/H ratio is 0.75 or more.

When the D/H ratio is less than 0.75, the piles are not embedded deeply enough to develop the fixed condition; consequently, they will rotate to a degree when loads are applied. The amount of rotation is a function of the restraint developed by the actual pile embedment. The degree of restraint decreases and rotation increases as the D/H ratio becomes smaller.

When rotation occurs, bending stresses are reduced but overall pile capacity is reduced as well, and in a disproportionate amount. The procedure used by the Division of Structures to estimate pile capacity when the embedded length is insufficient to develop the fixed condition is discussed in Section 7-3.04, Field Evaluation of Pile Capacity.

As noted above, the Division's method of analysis assumes that pile embedment is sufficient to develop the fixed condition. This is not an unreasonable assumption because, for most soil types, the penetration needed to obtain bearing will develop pile fixity as well. However, while this assumption may be true in general, it is not true in all cases; consequently, when timber pile bents are to be used, Division of Structures policy requires that approval of the design be contingent on the piles actually penetrating to the depth assumed in the analysis.[3]

7-3.02B Point of Pile Fixity

Assuming adequate penetration, the depth to the point of fixity is a function of soil stiffness and the diameter of the pile at the ground line. The relationship is:

$$y = (k)\,(d)$$

where y is the distance (depth) from ground line to the point of fixity, k is the soil stiffness factor, and d is the diameter of the pile at the ground line.

A widely accepted rule-of-thumb assumes that the point of fixity is located about four pile diameters below the ground surface for soil conditions ranging from medium hard to medium soft, and this assumption has been verified by recent load tests. Accordingly, assuming the depth of-pile fixity as four pile diameters (which corresponds to a k factor of 4.0) will be satisfactory for most soil types. For soft, yielding soils such as bay mud, this figure should be increased up to a maximum of six diameters.

Consideration may be given to raising the assumed point of fixity when piles are driven into very firm soils; however, caution is advisable because the driving of piles into any type of soil will tend to disturb the top few feet of the surrounding material.

An alternative approach uses information obtained from the Log of Test Borings sheet. The average of the penetrometer readings for the portion of the log equal to the depth of pile penetration, adjusted by eliminating spikes, gives an indication of the relative soil stiffness. With this average value, a soil stiffness factor can be obtained graphically from the Soil Factor Chart shown in Figure 7-12. As a precaution, however, keep in mind that while this method may appear sophisticated, it does not ensure a more accurate result. As a practical approach, use of the four-diameter rule-of-thumb will simplify analysis without sacrificing accuracy except in the case of very soft soils.

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[3] As an example, if the above-ground height of a given bent. is 20 feet, approval of the design should be contingent on the piles penetrating at least 15 feet when they are driven, and this condition of approval should be noted on the falsework drawings.

703.02C Driving Tolerance

Unless the piles are carefully driven, it will be necessary to pull the top of each pile into line before setting the pile cap. Pulling the top of a pile from its driven position to its final position under the cap produces a bending moment which must be, considered in the analysis. If the piles are appreciably out of line, the resulting bending stress may reduce pile capacity substantially.

Similarly, any deviation of the top of the pile in its final position from a vertical line through the point of pile fixity will result in an eccentric loading condition that also reduces pile capacity. Vertical load eccentricity, often referred to as pile "lean", does not necessarily occur because a pile is pulled. It is an independent loading condition that occurs whenever the top of a pile in its final position under the cap is not centered around a vertical line through the point of pile fixity.

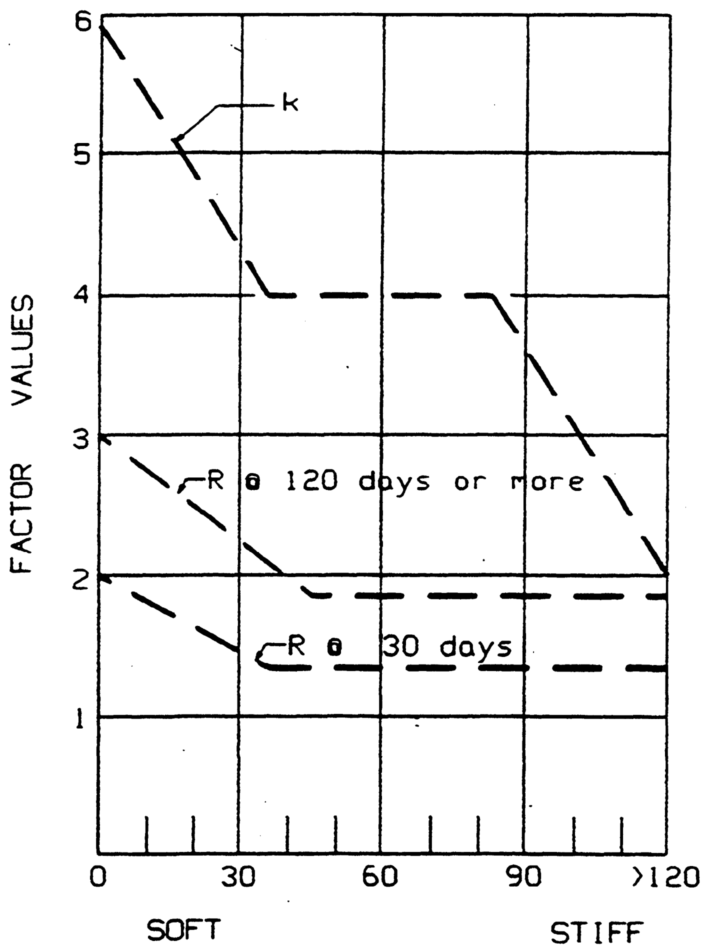
When investigating pile capacity, keep in mind that pile pull and pile lean are independent loading conditions. Either condition has the potential to reduce pile capacity substantially, and the adverse effect of both conditions must be considered in the design of timber pile bents. To ensure that they are considered, the specifications require the allowable driving tolerance for both conditions (maximum pull and maximum lean) to be shown on the falsework drawings.

7-3.02D Soil Relaxation Factor

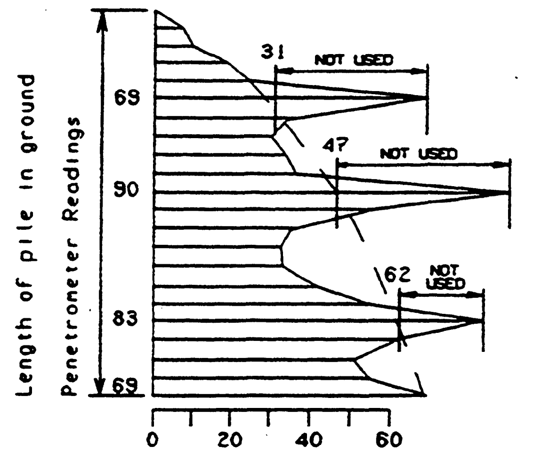
The force required to pull the top of a pile from its driven position to its final position under the cap causes the pile to bend, which in turn produces pressure on the soil below the ground surf ace. With time, the soil will yield under this pressure, allowing the pile to straighten to a degree. The yielding of the soil, called soil relaxation, lowers the point of fixity, which lengthens the pile column and reduces the bending stress proportionally.

In the analysis, the effect of soil relaxation is accounted for by a soil relaxation factor. The value of the soil relaxation factor in a given situation is a function of soil type and the length of time between the initial pull and application of the vertical load. These relationships are shown graphically in the Soil Factor Chart in Figure 7-12.

For the typical bridge project, a duration of time of about one month between the initial pull and application of at least a part of the vertical load is a reasonable expectation. As shown on the Soil Factor Chart, for a one-month duration of time, the soil



Average Penetrometer Readings



Sample Penetrometer Log

Another useful guideline for assigning a relative stiffness of the soil is to use the penetrometer test logs which are shown on the log of test boring plan sheets.

An average value is determined, using the portion of the log equal to the depth of pile penetration. Individual extremes (peaks) are adjusted.

This is an index of the relative stiffness of soil.

Sum adjusted readings = 816
22 Readings
816/22 = 37 Average Pen. Reading

Soil Factor Chart

FIGURE 7-12

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relaxation factor, "R", is about 1.25 for soil conditions ranging from hard to medium soft. For softer soils the value may be increased, up to a maximum of 2.0 for very soft, yielding soils such as bay mud.

If it is known ahead of time that the piles will remain unloaded for an extended period after being pulled, consideration may be given to increasing the numerical value of the soil relaxation factor. As shown on the Soil Factor Chart, the recommended increase-is proportional to time, from 10 percent for two months up to a maximum of 50 percent for four months or longer.

7-03.02E Modulus of Elasticity

The specifications establish the upper limit for the modulus of elasticity for timber at 1.6 x 10^6 psi. This is a reasonable value for the seasoned material typically used for falsework construct ion; however, a lower value may be more realistic for timber piles if relatively green material will be used.

When the nature of the material is unknown when the analysis is made, assume a value for E of 1.6 x 10^6 psi. This value gives conservative results for unseasoned timber; therefore, its use is appropriate when the actual character of the pile material (green or seasoned) is not known

If green piles will be used, and if the contractor so requests, the analysis may be based on a lower E value. Keep in mind, however, that the modulus of elasticity of a given material can be determined only by a load test; it cannot be determined by observation. Accordingly, Division policy requires load test data to be furnished by the contractor to verify the actual modulus value in any case where a value less than 1.6 x 10^6 psi is to be used.

7-3.02F Pile Diameter

Division of Structures policy requires falsework drawings to include enough information to enable the engineer to make a stress analysis, and this requirement applies to pile bents as well as other elements of the falsework system. In the case of timber piling, however, the exact dimensions may not be known ahead of time. In view of this, it is customary to base the design on minimum dimensions (minimum tip and butt diameter, minimum penetration, etc.) and to show these minimum dimensions on the falsework drawings.

When investigating pile capacity using contractor-furnished minimum dimensions, keep in mind that pile bents respond to applied loads in a different manner than other components of the falsework system. For example, if the actual diameter of the driven piles is larger than the diameter assumed in the analysis, vertical load-carrying capacity will be increased, as will the ability of the piles to withstand the adverse effect of pile lean. Other factors being equal, however, a large diameter pile cannot be pulled as far as a smaller pile. If the bending stress caused by pulling is a significant factor in the analysis, any pile having a larger ground line diameter than originally assumed may, in reality, have a lower overall load-carrying capacity.

Pile diameter has a greater influence on pile capacity than any other single factor, and the value used in the analysis should be selected with this fact in mind.

7-3.03 Analysis of Timber Pile Bents

To facilitate analysis of timber pile bents, the Division of Structures has adopted an empirical procedure which is based on the results of research involving full-scale load tests on driven timber piles. The test report concludes that evaluation of pile capacity using ultimate load factors will provide a higher degree of correlation with test results than will conventional analysis using a fixed level of working stresses.

To avoid a forced compliance with working stress values that appear overly conservative in the light of falsework requirements, the Division has developed a modified combined stress expression which, when used with an empirical procedure to determine the effect on pile capacity when driven piles are pulled into line, gives results that are in reasonably close agreement with the test results. Applicability of the Division's procedure has been confirmed by mathematical analysis using the computer pile shaft program currently used to design pile foundations in permanent work.

In essence, the Division's procedure is as follows:

1. Calculate the bending stress in the pile at the time the pile is pulled into position, using the maximum allowable pile pull value shown on the falsework drawings. (This stress is called the "initial" bending stress.)

2. Calculate the bending stress remaining in the pile after soil relaxation has taken place. (This stress is called the "relaxed" bending stress.)

3. Calculate the bending stress caused by vertical load eccentricity, using the maximum allowable value for pile lean shown on the falsework drawings.

4. Calculate the bending stress caused by the horizontal design load; calculate the lateral deflection of the pile bent and the bending stress caused by additional vertical load eccentricity resulting from that deflection. (This step is not required unless the L/d ratio exceeds 8. See Section 7-3.03C, Effect of Horizontal Loads.)

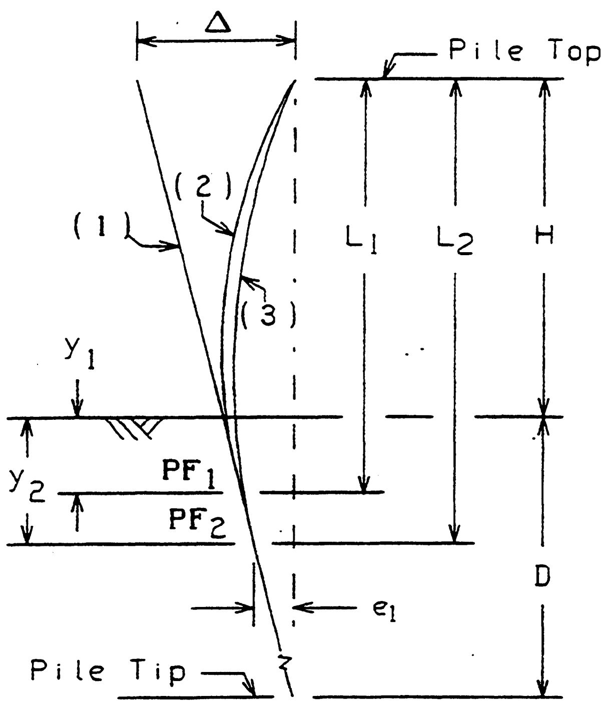
5. Calculate the P-delta deflection for the horizontal design load and, if applicable, for pile lean; calculate the bending stress resulting from the P-delta deflection. (This step is not required unless the L/d ratio exceeds 15. See Section 7-3.03D, Effect of P-delta Deflection.)

6. Calculate the compressive stress in the pile.

7. Enter the appropriate values in the combined stress expression to verify the adequacy of the design.

7-3.03A Effect of Pile Pull

Determining the bending stress that occurs when a pile is pulled is a two-step process. The first step calculates the stress produced by the initial pull. The second step calculates the stress remaining in the pile when the loads are applied.



(1) - driven position

(2) - initial pulled position

(3) - relaxed position

- **H - pile height, from ground line to top of pile, in feet**
- **D - pile embedment, from ground line to pile tip, in feet**
- **PF_1- initial point of pile fixity (i.e., when pile is pulled)**
- **PF_2- relaxed point of pile fixity (i.e., after soil relaxation takes place)**
- **L_1- initial length of pile column, in feet, from PF_1 to top of pile**
- **L_2- relaxed length of pile column, in feet, from PF_2 to top of pile**
- **Y_1- depth, in feet, from ground line to PF_1**
- **Y_2- depth, in feet, from ground line to PF_2**
- **Δ - maximum allowable pile pull, in inches, shown on the falsework drawings**
- **e_1- pile eccentricity = maximum allowable pile lean, in inches, shown on the falsework drawings**

FIGURE 7-13

Refer to Figure 7-13 for formula nomenclature and definition of terms used in the analysis. The procedure is as follows:

1 . Assume a ground line diameter using the minimum butt and tip diameters shown on the falsework drawings, the height of the bent from ground line to cap, and the estimated pile penetration. (See Section 7-3.02F, Pile Diameter.)

2 . Using the assumed ground line diameter, calculate the cross-sectional area, section modulus, and moment of inertia.

3 . Assume a value for the modulus of elasticity. (Caution: see Section 7-3.02E, Modulus of Elasticity.)

4. Determine the depth below ground line to the initial point of pile fixity. (See Section 7-3.02B, Point of Pile Fixity.)

5 . Determine the soil relaxation factor to be used in the analysis. (See Section 7-3.02D, Soil Relaxation Factor,)

6. Calculate values for L_1 and L_2 as shown in Figure 7-13.

$$L_1 = H + Y_1 \text{ and } L_2 = H + Y_2$$

In the formulas, L_1 is the length of the pile column when the pile is pulled initially, Y_1 is the depth to the initial point of fixity, L_2 is the length of the column after soil relaxation takes place, and Y_2 is the depth to the relaxed point of fixity. (Note that $Y_2 = Y_1$ multiplied by the soil relaxation factor.)

7. Calculate the force (F_1) required to pull the top of the pile from its driven position to its final position under the cap.

$$F_1 = \frac{3EI\Delta}{(12L_1)^3}$$

where the value for Δ is the -maximum allowable distance the top of the pile may be pulled, in inches, as shown on the falsework drawings, E is 1,600,OOO psi (unless a lower value has been selected for the analysis) and I is the moment of inertia from step 2.

8 .Calculate the initial bending stress $f_{bp(1)}$ in the pile.

$$f_{bp(1)} = \frac{F_1(12L_1)}{S}$$

where S is the section modulus from step 2.

For evaluation of pile adequacy, Division of Structures policy limits the calculated bending stress caused by the initial pile pull to 4000 psi.

9. Calculate the force (F_2) required to keep the top of the pile in its pulled position under the cap after all soil relaxation has occurred.

$$F_2 = \frac{3EI\Delta}{(12L_2)^3} = F_1(L_1)^3/(L_2)^3$$

10. Calculate the bending stress ($f_{bp(2)}$) remaining in the pile after soil relaxation has taken place.

$$f_{bp(2)} = \frac{F_2(12L_2)}{S}$$

7-3.03B Adequacy of Diagonal Bracing

For analysis, pile bents are classed as either braced or unbraced depending on the degree of rigidity provided by the bracing system. In addition, a bent is "braced" for analysis if it is stabilized by external support or if the horizontal forces are carried across the bent, as is often the case in the longitudinal direction.

To be classed as a braced bent, diagonal bracing must meet the following criteria:

1. Transverse bracing must comply with the provisions in Section 5-1.03, Diagonal Bracing. In addition, the frame must include a horizontal member installed in a plane through the connections at the bottom of the lowest tier of bracing. The horizontal member must be fastened to each pile in the bent with a bolted connection.

2. Longitudinal bracing, if used to stabilize the bent, must comply with the criteria for transverse bracing in the preceding paragraph. If longitudinal forces are carried across the bent, the design must comply with the criteria in Section 5-1.04, Longitudinal Stability.

7-3.03C Effect of Horizontal Loads

In a typical pile bent diagonal bracing will be installed between the cap and a point near the ground or water surface. Within the limits of a properly designed and constructed bracing system, the bracing will resist horizontal forces in the same manner as the bracing in any other framed bent. Below the bracing, however, a horizontal load will deflect the piles, and this deflection will produce a bending moment. It is evident, then, that the ability of a pile bent to resist the horizontal design load is a function of the contribution to frame rigidity provided by the diagonal bracing and the stiffness of the individual piles.

Other factors being equal, the effect on system stability of bending stresses produced by the horizontal design load is a direct function of the unsupported length of the pile column. (For this case the unsupported length is the vertical distance between the relaxed point of pile fixity and the bolted connection at the bottom of the lowest tier of diagonal bracing.)

To ensure uniformity, Division policy requires consideration of the bending stress produced by application of the horizontal design load in all cases where the ratio of the unsupported pile length to the pile diameter. at the ground line (expressed as L_u/d exceeds 8. For typical pile diameters and average soil conditions, this value corresponds to a distance of about two feet between the ground surface and the bottom of the bracing.

7-3.03D Effect of P-delta Deflection

When an unsupported pile is subjected to both horizontal and vertical loads, the pile will deflect laterally in the direction of the applied horizontal load, This lateral deflection moves the original point of application of the vertical -load, and the resulting horizontal displacement produces an eccentric loading condition. (See "x" in Figure 7-15 on page 7-40.)

The total vertical load eccentricity that occurs when the-pile column is deflected laterally is the sum of the deflection caused by the horizontal load and the additional deflection caused by bending which occurs as a consequence of the vertical load acting on the pile in its deflected position. The additional deflection of the pile column under the applied vertical load, and the corresponding increase in the bending stress, is often referred to as the "P-delta" effect.

The total deflection resulting from the combined action of a horizontal and a vertical load cannot be calculated directly since it is the sum of a converging mathematical series. However, it may be approximated by incremental addition using the iterative procedure and formulas shown in Figure 7-15. (See also Example Problem 14C in Appendix D.)

Additional bending due to the P-delta effect also occurs when a vertical load is applied to an unsupported pile that is leaning in any direction. When the load is applied, the pile column will deflect laterally in the direction of the pile lean. In this case the deflecting force is the horizontal component of the vertical load reaction acting along the axis of the out-of-plumb pile.

When the unsupported length of the pile column is small, the lateral deflection due to the P-delta effect will be small as well; consequently, the stress produced by additional bending in the pile may be neglected. As the unsupported length increases, however, the deflection also increases so that at some point the resulting bending stress must be considered in the analysis.

Division of Structures policy requires consideration of bending due to P-delta deflection when the ratio of the unsupported pile length to the ground line pile diameter (L_u/d) exceeds 15. While the use of a limiting L_u/d ratio of 15 is considerably more liberal than is typically the case for frame analysis, this procedure is satisfactory for pile bents because of the inherent stability provided by the driven piles.

When considering the effect of P-delta deflection, keep in mind that the "H" value used to begin the iterative calculation is the total horizontal force produced by the combined application of the horizontal and vertical design loads. Thus H is the sum of the horizontal design load and the horizontal component of the vertical design load acting on the pile in its leaning position.

7-3.03E Adequacy of Braced Bents

For evaluation of design adequacy, braced bents are divided into three categories, or bent types, depending on the L_u/d ratio of the unsupported pile column, as follows:

Type I - $L_u/d \leq 8$.

Type II - $8 > L_u/d \leq 15$.

Type III - $L_u/d > 15$.

The procedure to be followed depends on the type of bent under consideration, as explained in the following sections.

7-3.03E(1) Type I Pile Bents

Type I pile bents are bents where all bracing conforms to the criteria in Section 7-3.03B, Effect of Diagonal Bracing, and the L_u/d ratio of the pile column is 8 or less.

In a Type I bent the bending stress produced by the horizontal design load may be neglected, and the modified combined stress expression is:

$$\frac{f_{bp(2)} + 2f_{be(1)}}{3F_b} + \frac{2f_c}{3F_c} \leq 1.0$$

where $f_{bp(2)}$ = the bending stress remaining in the pile after soil relaxation takes place.

$f_{be(1)}$ = the bending stress due to vertical load eccentricity occurring as a consequence of pile lean.

f_c = the stress in compression parallel to the grain (axial compression) due to the vertical load.

F_b = the allowable working stress in bending.

F_c = the allowable working stress in compression parallel to the grain.

In the combined stress expression, the numerical coefficients "2" and "3" are the load factor and the working stress modification factor, respectively.

As noted, a satisfactory condition is indicated when the value of the combined stress expression is not greater than 1.0.

The procedure for evaluating the adequacy of a braced bent using the modified combined stress expression is as follows:

1. Calculate $f_{bp(2)}$ following the procedure explained in Section 7-3.03A, Effect of Pile Pull.

2. Calculate the bending stress due to vertical load eccentricity.

$$f_{be(1)} = (P_v)(e_1)/S$$

where $f_{be(1)}$ is the bending stress; P_v is the vertical design load, in pounds; e_1 is the maximum pile lean shown on the falsework drawings, in inches; and S is the pile section modulus.

3. Calculate the stress due to axial compression.

$$f_c = P_v/A$$

where f_c is the compressive stress and A is the area of the pile at the ground line.

4. When longitudinal forces produced by the horizontal design load are carried across the bent, the unsupported length of the pile column in the longitudinal direction, because of the absence of bracing, will be greater than in the transverse direction. In such cases it is necessary to determine the allowable compressive stress using the column formula given in the specifications:

$$F_c = \frac{480{,}000}{(L_u/d)^2} \text{ but not more than 1600 psi.}$$

In the column formula, F_c is the maximum allowable compressive stress parallel to the grain; L_u is the unbraced length, in inches; and d is the least dimension, in inches, measured normal to the plane of bending.

Note that the column formula was developed for a square or rectangular section. For a round section such as a timber pile, the least dimension "d" is the length of the side of a square having the same cross-sectional area as the pile under consideration -- not the pile diameter. (See Chapter 4, Section 4-2.08, Timber Posts, for the derivation of the column formula.)

Pile area should be calculated using the ground line diameter. It is unnecessary to refine the calculation by considering pile taper.

The column formula given in the specifications is valid only when the modulus of elasticity for the member under consideration is 1,600,OOO psi. If a lower value is being used in the analysis, the allowable stress given by the formula must be reduced by the ratio of the modulus value being used to 1,600,OOO.

When E is 1,600,OOO psi the column formula will give an allowable compressive stress value below 1600 psi for L_u/d ratios greater than about 17.3. The limiting L_u/d ratio will be reduced below 17.3 for lower E values.

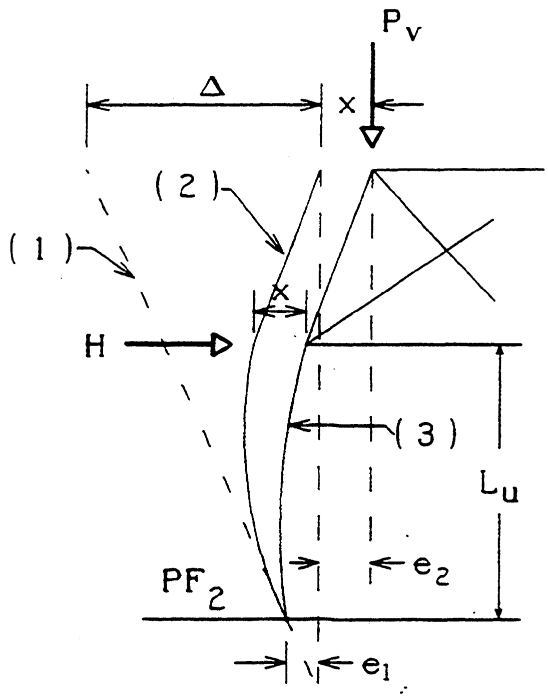
5 .Enter the appropriate values and solve the combined stress expression.

7-3.03E(2) Type II Pile Bents

Type II pile bents are bents where all bracing conforms to the criteria in Section 7-3.03B, Adequacy of Diagonal Bracing, and the L_u/d ratio of the pile column is greater than 8 but not more than 15. For Type II bents it is necessary to consider the effect of horizontal forces but not P-delta deflection,

When calculating stresses and deflections in the pile column, the bent will be considered as a braced frame within the vertical limits of the bracing, and the horizontal design load will be applied in a plane through the bolted connections at the bottom of the bracing.

For analysis, the unsupported length of the pile column is the vertical distance between the relaxed point of pile fixity and the connections at the bottom of the lowest tier of bracing, and the pile column is assumed to be fixed against rotation and translation at the relaxed point of fixity and free to rotate and translate with the frame at the connection at the bottom of the bracing.



Δ - **maximum allowable pile pull**

P_v - **vertical design load**

H - **horizontal design load**

x - **horizontal displacement after applying the horizontal design loads**

L_u - **unsupported length of pile column**

PF_2 - **relaxed point of pile fixity**

e_1 - **original vertical load eccentricity**

e_2 - **eccentricity due to horizontal displacement**

(1) - **driven position of pile**

(2) - **relaxed position of pile**

(3) - **position of pile after applying the horizontal design loads**

FIGURE 7-14

Figure 7-14 is a schematic representation of a pile in a Type II pile bent before and after the horizontal design load is applied. Design adequacy is evaluated as follows:

1. Calculate the bending stress remaining in the pile after soil relaxation takes place, the bending stress produced by vertical load eccentricity due to pile lean and the stress due to axial compression and, if necessary, the allowable compressive stress. For these calculations follow the procedure for Type I bents explained in the preceding section.

2. **Calculate the bending stress produced by the horizontal design load.**

$$f_{bH} = (H)(12L_u)/S$$

where f_{bH} is the bending stress; H is the horizontal design load, in pounds; L_u is the unsupported length of the pile column, in feet; and S is the pile section modulus.

3. Calculate the lateral displacement that occurs when the horizontal design load is applied to the pile column. (See "x" in Figure 7-14.)

$$x = \frac{(H)(12L_u)^3}{3EI}$$

where x is the displacement, in inches; E is the modulus of elasticity; and I is the moment of inertia of the pile column.

4. Calculate the bending stress due to additional vertical load eccentricity caused by the horizontal displacement. (The additional vertical load eccentricity is numerically equal to the horizontal displacement. See Figure 7-11.)

$$f_{be(2)} = (P_v)(e_2)/S$$

where $f_{be(2)}$ is the bending stress; P_v is the vertical design load, in pounds; and e_2 is the additional vertical load eccentricity caused by the horizontal displacement, in inches.

5. Enter the stress values and solve the combined stress expression. For this case the expression becomes:

$$\frac{f_{bp(2)} + 2f_{be(1)} + 2[f_{bH} + f_{be(2)}]}{3F_b} + \frac{2f_c}{3F_c} \leq 1.0$$

where f_{bH} is the bending stress produced by the horizontal design load and $f_{be(2)}$ is the bending stress produced by vertical load eccentricity resulting from lateral displacement of the pile at the point of application of the horizontal design load.

As shown in the combined stress formula, all bending stresses are additive. This occurs because, when evaluating the adequacy of pile bent designs, the horizontal design load is assumed to act in the direction that produces the highest combined bending stress in the pile column.

7-3.03E(3) Type III Pile Bents

Type III pile bents are bents where all bracing conforms to the criteria in Section 7-3.03B, Adequacy of Diagonal Bracing, and the L_u/d ratio of the pile column exceeds 15. For Type III bents it is necessary to consider the bending stress produced by P-delta deflection. The procedure is as follows:

1. Calculate the bending stress remaining in the pile-after soil relaxation takes place and the bending stress due to pile lean.

2 . Calculate the bending stress due to application of the horizontal design load. (See step 2 in the preceding section.)

3 . Calculate the horizontal component of the vertical load reaction when the vertical load is applied to the pile in its initial leaning position.

$$H_e = (P_v)(e_1)/12L_2$$

where H_e is the horizontal component, in pounds; P_v is the vertical load, in pounds; e_1 is the maximum allowable pile lean shown on the falsework drawings, in inches; and L_2 is the length of the pile when P_v is applied, in feet.

4. Both the horizontal design load [H] and the horizontal component of the vertical design load $[H_e]$ act on the pile to produce additional vertical load eccentricity. Therefore, these two forces are added to obtain the horizontal force to use in the P-delta calculation.

5 . Using the total horizontal force from step 4, calculate the total horizontal displacement (e3) following the procedure explained in Section 7-3.03D, Effect of P-delta Deflection, and illustrated in Figure 7-15 Example Problem 14C in the appendix.

6 . Calculate the bending stress produced by the horizontal displacement calculated in step 5.

$$f_{be(3)} = (P_v)(e_3)/S$$

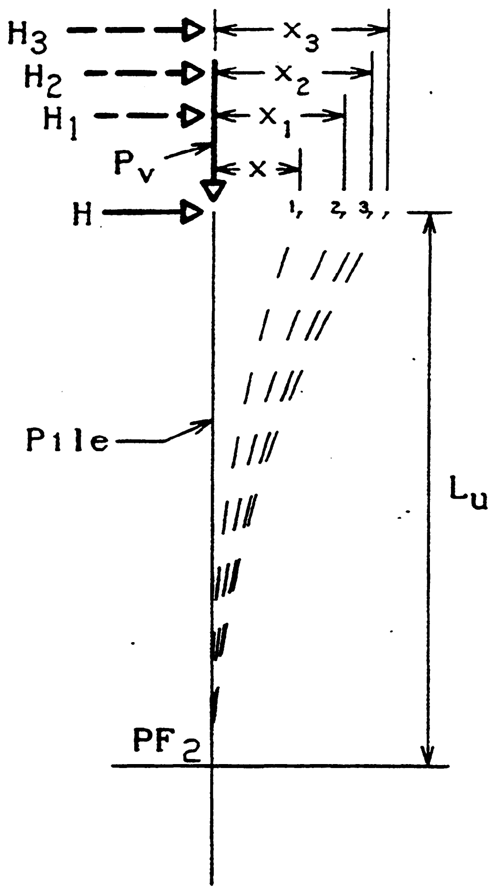
where $f_{be(3)}$ is the bending stress; P_v is the vertical design load, in pounds; e_3 is the P-delta deflection due to the combined effect of the horizontal design load and pile lean, in inches; and S is the pile section modulus.

7. Calculate the stress due to axial compression.

8 . Determine the allowable compressive stress using the column formula given in the specifications. (See the discussion in Section 7-3.03E(l), Type I Pile Bents.)

9 . Enter the stress values and solve the combined stress expression. For this case the expression becomes:

$$\frac{f_{bp(2)} + 2f_{be(1)} + 2[f_{bH} + f_{be(3)}]}{3F_b} + \frac{2f_c}{3F_c} \leq 1.0$$



L_u - unsupported length, in feet

PF_2 - relaxed point of pile fixity

P_v - vertical design load, in pounds

H - actual horizontal force, in pounds

x - horizontal displacement, in inches, due to H

$$x = \frac{(H)(12L_u)^3}{3EI}$$

x_1 - total horizontal displacement, in inches, when P_v is applied at point (1)

H_1 - fictitious force required to produce x_1

$$H_1 = H + \frac{(P_v)(x)}{12L_u}$$

$$x_1 = \frac{(H_1)(12L_u)^3}{3EI} = \frac{(H_1)(x)}{H}$$

x_2 - total horizontal displacement, in inches, when P_v is applied at point (2)

H_2 - fictitious force required to produce x_2

$$H_2 = H_1 + \frac{(P_v)(x_1-x)}{12L_u}$$

$$x_2 = \frac{(H_2)(12L_u)^3}{3EI} = \frac{(H_2)(x)}{H}$$

x_3 - total horizontal displacement, in inches, when P_v is applied at point (3)

H_3 - fictitious force required to produce x_3

$$H_3 = H_2 + \frac{(P_v)(x_2-x_1)}{12L_u}$$

$$x_3 = \frac{(H_3)(12L_u)^3}{3EI} = \frac{(H_3)(x)}{H}$$

The value for "H" is the actual horizontal force being used in the analysis. In the formulas, all horizontal force values are in pounds. The iteration may be discontinued when the calculated total displacement exceeds the previously calculated total displacement by less than 5 percent.

FIGURE 7-15

7-3.03F Investigation of Longitudinal Stability

The discussion in Sections 7-3.03E(2) and 7-3.03B(3) has focused on the procedures used to evaluate the adequacy of Type II and Type III pile bents, respectively, when subjected to horizontal forces applied in the transverse direction, or parallel to the plane of the bracing. However, the falsework system must be capable of resisting horizontal forces applied in any direction; therefore, the pile bent analysis must consider longitudinal stability as well.

In most falsework designs, longitudinal stability is achieved by carrying the horizontal design load across the falsework bents to a point of external support, such as an abutment or column that is part of the permanent structure. Such designs must comply with the provisions in Section 5-1.04, Longitudinal Stability.

When pile bents are designed in accordance with Section 5-1.04, longitudinal application of the horizontal design load need not be considered in the pile analysis. If, however, longitudinal stability is provided by some other means, such-as diagonal bracing between two or more adjacent bents, the ability of the piles to resist the horizontal design load must be investigated.

Diagonal bracing used in the longitudinal direction must comply with the provisions Section 7-3.03B, Adequacy of Diagonal Bracing, including the requirement for a horizontal member between the connections at the bottom of the bracing. The horizontal member must be sized to carry the horizontal design load as a column. If the member is not so designed, or if the bracing fails to comply with Section 7-3.03B in any other aspect, the bent will be considered "unbraced" for analysis in the longitudinal direction.

When the longitudinal bracing is adequate, the horizontal design load will be applied in a plane through the connections at the bottom of the bracing, and the stresses and deflections in the pile column below the bracing will be calculated as provided in Sections 7-3.03E(2) and 7-3.036(3) for Type II and Type III bents, respectively. However, there are several additional factors that must be kept in mind when making the longitudinal analysis, as discussed in the following paragraphs.

First, when the connections at the bottom of the longitudinal bracing are not located in the same horizontal plane as the connections at the bottom of the transverse bracing, the length of the pile column below the bracing will be different for the longitudinal and transverse directions, and this may result in different bent types in the two directions. For example, a given bent may be Type II for analysis in the transverse direction, but because of the bracing location, the bent may be Type III when viewed in the longitudinal direction.

Second, all bents that are connected by longitudinal bracing will deflect together when the horizontal design load isapplied in the longitudinal direction; consequently, the <u>total</u> horizontal design load acting on the <u>system</u> must be apportioned between the bents. When the piles in each bent have similar properties, each bent will resist one-half of the total load, but this will result in a different design load longitudinally than transversely unless each bent carries the same vertical load.

Consider the bent and bracing arrangement shown schematically in Figure 7-16. For braced bent D-E, the horizontal design load in the transverse direction is 0.02P and 0.03P at bents D and E, respectively. In the longitudinal direction, however, the design load is (l/2)(0.02) (P + 1.5P) = 0.025P at both bent D and bent E.

Even where the vertical load is the same at all bents under consideration, the horizontal design load is not necessarily the same. For example, at bent A-B in Figure 7-16, the horizontal design load in the transverse direction is the same for both bents. In the longitudinal direction, however, some portion of the horizontal load generated by the vertical load applied to free-standing bent C will be carried over to bent B, and this produces a greater horizontal design load longitudinally than transversely at each -bent in the A-B system.

Finally, differences in the applied vertical load on adjacent braced bents may create a situation where the piles in the two bents will have different physical properties, as would be the case at bents D-E and F-G, for example, if bents E and F require a larger diameter pile to carry the heavier vertical load. In such bents, the total horizontal load acting on the system must be apportioned between the bents in a manner that reflects the relative stiffness of the piles in each bent, rather than equally between the bents.

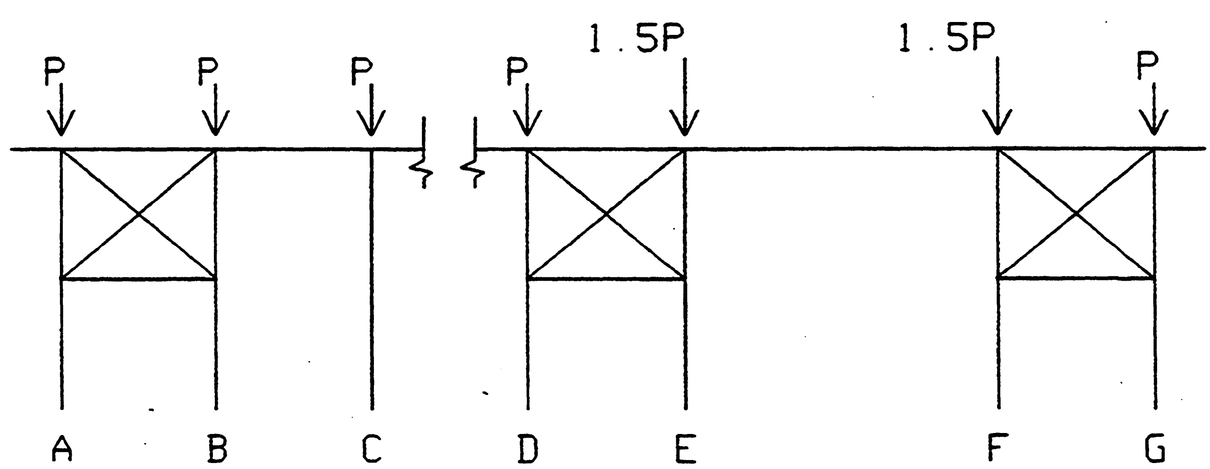


FIGURE 7-16

7-3.03G Analysis of Unbraced Bents

An unbraced bent is any bent where diagonal bracing is not used and which is not stabilized by external support. For analysis, the term "unbraced bent" also includes any braced or partly braced bent where the bracing does not meet the criteria in Section 7-3.03B, Adequacy of Diagonal Bracing.

When calculating the deflection and bending moment in an unbraced bent, the horizontal design load will be applied in a plane at the top of the piles, and the piles will be analyzed as unsupported cantilevers extending from the relaxed point of pile fixity to the pile cap.

Except for the point of application of the horizontal design load, the adequacy of unbraced bents is evaluated in the same manner as braced bents. Follow the procedure for the appropriate pile bent type as discussed in Section 7-3.03E, Adequacy of Braced Bents.

7-3.04 Field Evaluation of Pile Capacity

Because of the construction uncertainties associated with pile driving, piles in the driven position do not always attain the penetration assumed in the analysis. Additionally, unanticipated driving and/or site conditions may cause a driven pile to deviate from its planned position to a significantly greater degree than the allowable deviation assumed by the contractor and shown on the falsework drawings.

From a contractual standpoint, any pile that fails to reach the required penetration, or which deviates from its theoretical position to a greater extent than the allowable deviation shown on the falsework drawings, or which fails to meet any other design assumption, may be rejected without further evaluation because the construction work represented by that pile is not in conformance with the approved falsework drawings.

The above policy notwithstanding, circumstances may arise which in the engineer's judgment would warrant an evaluation of the actual load-carrying capacity of a particular pile in its driven condition. It is emphasized, however, that field personnel are not authorized to undertake any unilateral investigation of driven pile adequacy. When driven piles are not in conformance with design assumptions shown on the falsework drawings or noted on the drawings as a condition of design approval, no further evaluation is required or expected unless the contractor requests an evaluation, and submits a revised falsework drawing with supporting calculations showing that the pile or piles in the non-conforming as-driven condition are nevertheless capable of resisting the design loads.

The procedures used by the Division of Structures to estimate the capacity of piles which do not attain the penetration necessary to develop pile fixity, or which in their driven position exceed the allowable driving tolerances shown on the falsework drawings, are explained in the following sections.

Section 7-3.04A Failure to Attain Required Penetration

As discussed in Section 7-2.02A, Required Pile Penetration, the Division of Structures uses the ratio of the depth of pile penetration to the height of the pile above the ground surface (expressed as D/H) as the criterion to ascertain whether a given pile is driven deeply enough to develop the fixed condition. For analysis, pile fixity is assumed when the D/H ratio is 0.75 or more.

When driven piles do not attain the penetration necessary to assure the fixed condition, the procedure for analysis discussed in the preceding sections of this manual is not valid. However, the Division has developed an alternative procedure that may be used to estimate the load-carrying capacity of such piles.

The Division's alternative procedure assumes that any pile having a D/H ratio of less than 0.75 will rotate to a degree when the loads are applied. The amount of rotation is a function of the. restraint developed by the pile embedment actually obtained. The degree of restraint decreases and rotation increases as the D/H ratio becomes smaller; consequently, the procedure depends on the actual D/H ratio in a given situation, as explained in the following Sections.[4]

7-3.04A(l) Analysis for D/H Ratios Between 0.75 and 0.45

When the D/H ratio is less than 0.75 but not less than 0.45, the piles are capable of resisting some bending. The amount of bending resistance developed by a given pile is an inverse function of the degree of rotation. As the D/H ratio decreases between the limiting values, rotation increases and bending resistance and overall load-carrying capacity are reduced.

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[4] Reference to the chart in Figure 7-17 reveals that pile rotation will reduce the relative stiffness of a pile for all D/H ratios below 1.0, although the stiffness coefficient is too small to have an appreciable influence on pile capacity until the D/H ratio decreases to about 0.75. For this reason, the Division of Structures has selected 0.75 as a practical limiting D/H ratio for the fixed-condition assumption.

To account for the reduced overall load-carrying capacity when rotation occurs, the analysis applies a stiffness reducing coefficient when calculating the depth to the point of pile fixity. The stiffness reducing coefficient, or "Q", is obtained graphically from the chart in Figure 7-17, which shows Q values for D/H ratios from 0.45 to 1.0 for average and soft soils.

The procedure for estimating pile capacity is as follows:

1 . Determine the actual D/H ratio using the as-driven pile penetration. Using the actual D/H ratio, select "Q" from the chart in Figure 7-17.

2 . Using the Q value from step 1, calculate a new L_2 value.

$$\text{New } L_2 = H + (Q)(Y_2)$$

where Y_2 is the previously calculated depth to the relaxed point of pile fixity and the expression $(Q)(Y_2)$ is the depth to an adjusted point of fixity used in the analysis.

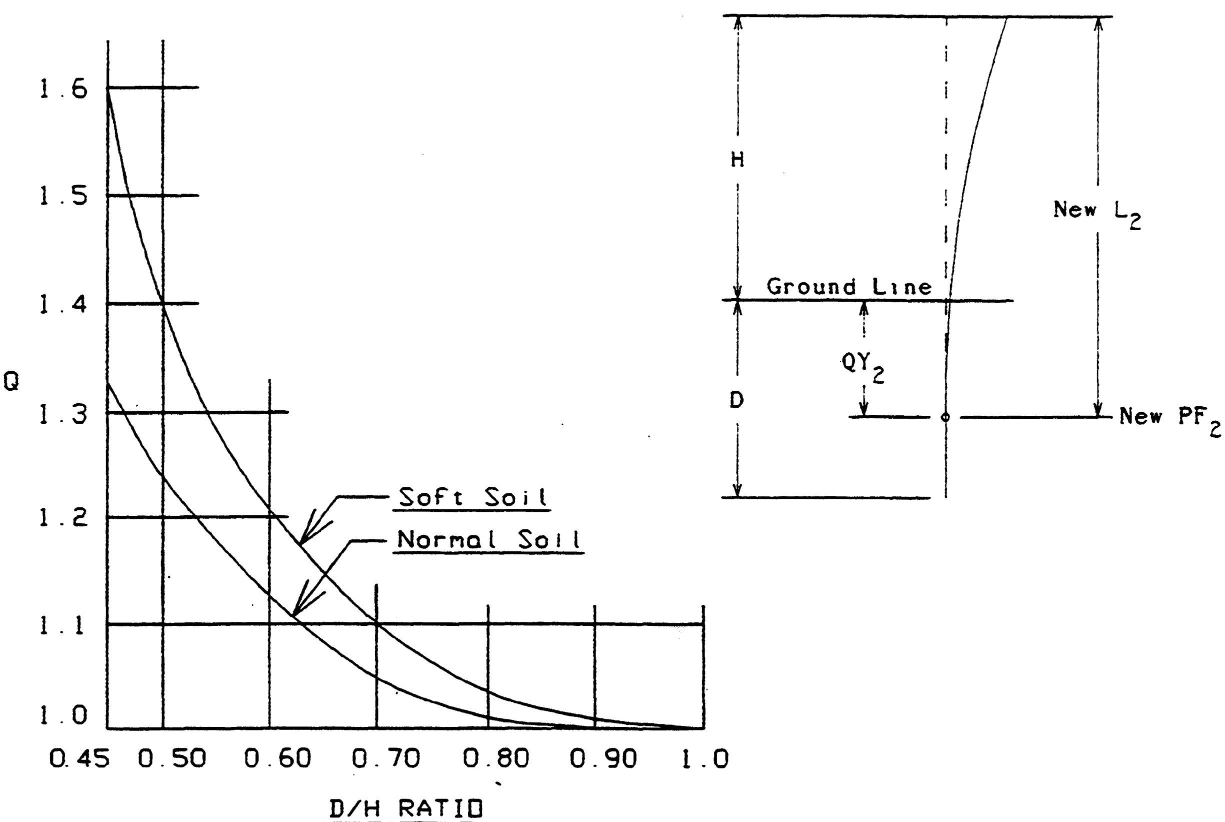


FIGURE 7-17

Note that it is unnecessary to calculate a new L_1 value because it is unnecessary to recalculate the bending stress that occurs during the initial pile pull. The smaller D/H ratio results in a longer L_1 column, which in turn produces a lower initial bending stress.

3. Using the new L_2, calculate a new unsupported length and a new (adjusted) L_u/d ratio. (The new unsupported length is the vertical distance between the bottom of the bracing and the ground surface plus the depth to the adjusted point of pile fixity [Q x Y_2] from step 2.)

   Use the new L_u/d ratio to determine the bent type for the pile capacity analysis.

4 . For a Type I bent use the new L_2 length and calculate new values for $f_{bp(2)}$ and $f_{be(1)}$.

5 . For a Type II bent, use the new L_2 to calculate new values for $f_{bp(2)}$ and $f_{be(1)}$, and the new L_u to calculate new values for f_{bH} and $f_{be(2)}$.

1 . For a Type III bent use the new L_2 to calculate new values for $f_{bp(2)}$ and $f_{be(1)}$, and the new L_u to calculate new values for f_{bH} and $f_{be(2)}$

Enter the new values obtained in steps 4, 5 or 6 as the case may be in the appropriate combined stress expression. The pile is adequate if the value of the expression is not greater than 1.0.

7-3.04A(2) Analysis for D/H Ratios Below 0.45

For D/H ratios below about 0.45, the ability of a given pile to resist pullback bending decreases rapidly and, as the theoretical point of contraflexure approaches the pile tip, pile restraining capability becomes highly subjective. Furthermore, as pile embedment decreases, the type of soil has a significantly greater influence on the ability of a pile to resist rotation.

For these reasons, piles having a D/H ratio of less than 0.45 are considered as incapable of developing a true point of fixity. When subjected to. a bending moment, such piles are assumed to be free to rotate but restrained against lateral translation at or very near the pile tip.

In view of the uncertainties associated with low D/H ratios, Division policy assumes that any pile having an actual D/H ratio less than 0.45 will be capable of carrying axial loads only, For such piles, any vertical load eccentricity and all horizontal forces must be resisted by bracing, external support or other piles in the system.

Section 7-3.04B Failure to Meet Driving Tolerances

In accordance with Division policy, bending stresses produced by the allowable driving tolerances (pile pull and pile lean values shown on the falsework drawings) are added when reviewing falsework designs for compliance with contract requirements. This procedure is necessary to ensure that the piles are not overstressed under the most adverse loading combination.

In practice, however, the pile pull direction may be opposite to the vertical load eccentricity caused by pile lean, in which case the adverse loading combination assumed in the analysis will not occur. When the pile pull direction is opposite to the vertical load eccentricity, the two bending stresses are compensating. Depending on the actual as-driven position, excessive pile pull in one direction may be offset by excessive lean in the opposite direction, so that the resulting combined stress is less than the allowable stress.

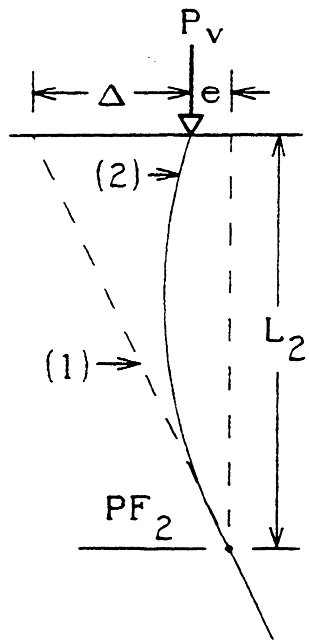
Refer to Figure 7-18 and note that "Δ" and "e" are the actual pull and lean distances for the driven position of a pile in a braced bent. Both distances exceed their respective allowable values for pile pull and pile lean shown on the approved falsework drawings. (Note: for the following general discussion, the direction of pile pull and the direction of pile lean are assumed to be in the same vertical plane.)

When calculating bending stresses for the as-driven position of a given pile, follow the procedures explained in Section 7-3.03, Analysis of Pile Bents, but use the actual pile pull and pile lean distances. Note, however, that for the as-driven analysis, it is also necessary to determine whether the bending stress values are positive or negative before solving the combined stress expression.

In accordance with standard sign convention, stress values are positive or negative depending on the direction of the bending moment applied at the relaxed point of pile fixity. A clockwise moment produces positive bending stress. Conversely, a counterclockwise moment produces negative bending stress. Therefore, in a Type I bent, the combined stress expression for the general case is:

$$\left| \frac{\pm f_{bp(2)} \pm 2f_{be(1)}}{3F_b} \right| + \frac{2f_c}{3F_c} \le 1.0$$

The vertical lines on either side of the bending stress fraction indicate that the absolute value of the fraction is to be used when solving the expression.



Δ - actual pile pull distance, in inches, for the as-driven pile

e - pile eccentricity = actual pile lean, in inches, for the as-driven pile

P_v - vertical design load

PF_2 - relaxed point of pile fixity (i.e., after soil relaxation takes place)

L_2 - relaxed length of pile column, in feet, from PF_2 to top of pile

(1)- as-driven position of pile

(2)- relaxed position of pile

FIGURE 7-18

Refer to Figure 7-18 and note that the pile pull, because it is clockwise, produces a positive bending stress. The vertical load eccentricity due to pile lean applies a counter-clockwise moment; therefore, the stress it produces is negative. For the pile in Figure 7-18, the combined stress expression looks like this:

$$\left| \frac{\pm f_{bp(2)} - 2f_{be(1)}}{3F_b} \right| + \frac{2f_c}{3F_c} \leq 1.0$$

Summarizing, when the as-driven position of a pile in a Type I bent exceeds the driving tolerances shown on the falsework drawings, the capacity of that pile may be estimated as follows:

1. Calculate the initial bending stress due to pile pull using the actual pull distance. If the calculated stress is less than the allowable stress of 4000 psi for the initial pull, calculate the relaxed bending stress.

2. Calculate the bending stress due to pile lean using the actual eccentricity distance.

3. Determine the direction of the applied bending moment at the relaxed point of pile fixity and the sign (positive or negative) of the two bending stresses.

4. Determine the stress due to axial compression. (Axial compression is not affected by the excessive pile pull or pile lean; consequently, the value to be used in this analysis is the value calculated for the design review.)

5. Enter the stress values and solve the combined stress expression. The load-carrying capacity of the pile in its driven position is satisfactory if the value of the combined stress expression is not greater than 1.0.

When the pile to be evaluated is in a Type II bent, it is also necessary to consider the effect of horizontal deflection. For a pile in a Type II bent, then, the combined stress expression for the general case is:

$$\left| \frac{\pm f_{bp(2)} \pm 2f_{be(1)}}{3F_b} \right| + \frac{2[f_{bH} + f_{be(2)}]}{3F_b} + \frac{2f_c}{3F_c} \leq 1.0$$

As shown in the expression, both the relaxed bending stress $[f_{bp(2)}]$ and the stress due to pile lean $[f_{be(1)}]$ may be either positive or negative depending on the direction of bending, while the sum of the bending stresses produced by the horizontal design load $[f_{bH} + f_{be(2)}]$ is positive. (Note that the H load bending stresses are always positive because, even though the horizontal design load may act from either direction, for analysis the horizontal load is applied from the direction that produces the highest combined bending stress.)

When the pile to be evaluated is in a Type III bent, the final term in the numerator of the bending stress fraction is replaced by $f_{be(3)}$ to account for the additional vertical load eccentricity produced by P-delta deflection.

The preceding discussion has assumed that pile pull and pile lean (and horizontal deflection, if applicable) are in the same plane. In actual practice, this would be an unlikely occurrence.

When the bending forces due to pile pull and pile lean act in different vertical planes, it is necessary to add the bending stress vectors geometrically and enter the resultant stress in the combined stress expression.

The procedure for evaluating pile capacity using vector analysis is explained in the following section. Keep in mind, however, that an analysis based on the assumption that pile pull and pile lean are in the same plane is conservative since, for a given pile, it gives a larger combined stress expression value than an analysis that considers the actual direction of application of the bending forces. Therefore, stress vectoring should not be necessary in all cases.

Determining in advance of analysis whether the relative direction of application of the bending forces is of sufficient importance to warrant consideration is a matter of engineering judgment. As a guide, if the angle between the two bending planes is small, say less than about 30 degrees, same plane bending may be assumed and the evaluation made on this basis. If the value of the combined stress expression is less than 1.0, the pile under consideration is adequate.

If the calculated value of the combined stress expression is greater than 1.0, judgment is required to determine whether reevaluation using vector analysis will result in a satisfactory condition. Generally, if the value is greater than 1.0 but only slightly greater, pile capacity should be reevaluated based on the actual direction of load application.

7-3.04B(l) Vectorins of Stresses

Figure 7-16 is a schematic plan view showing the location of the bottom of a pile, the top of the same pile in its driven and final (pulled) position under the cap, and the direction of pull and the direction of lean after pulling. Also-shown are stress vectors for the relaxed bending stress $[f_{bp(2)}]$ and the bending stress due to pile lean $[2f_{be(1)}]$, and the resultant of these two vectors. Note that the stress resultant is designated "f_{bR}".

In a braced bent, the procedure for evaluating pile capacity using stress vectoring is as follows;

1. Determine the direction of pull and the pull distance.
2. Calculate the initial bending stress due to the pile pull using the actual pull distance. If the calculated stress is less than the allowable stress of 4000 psi for the initial pull, calculate the relaxed bending stress.
3. Determine the direction of lean after the pile is pulled, and the magnitude of the lean.
4. Calculate the bending stress produced by vertical load eccentricity resulting from the pile lean using the actual eccentricity distance.
5. Multiply the value obtained in step 4 by the load factor coefficient of 2 to obtain the stress value to use in the resultant calculation.

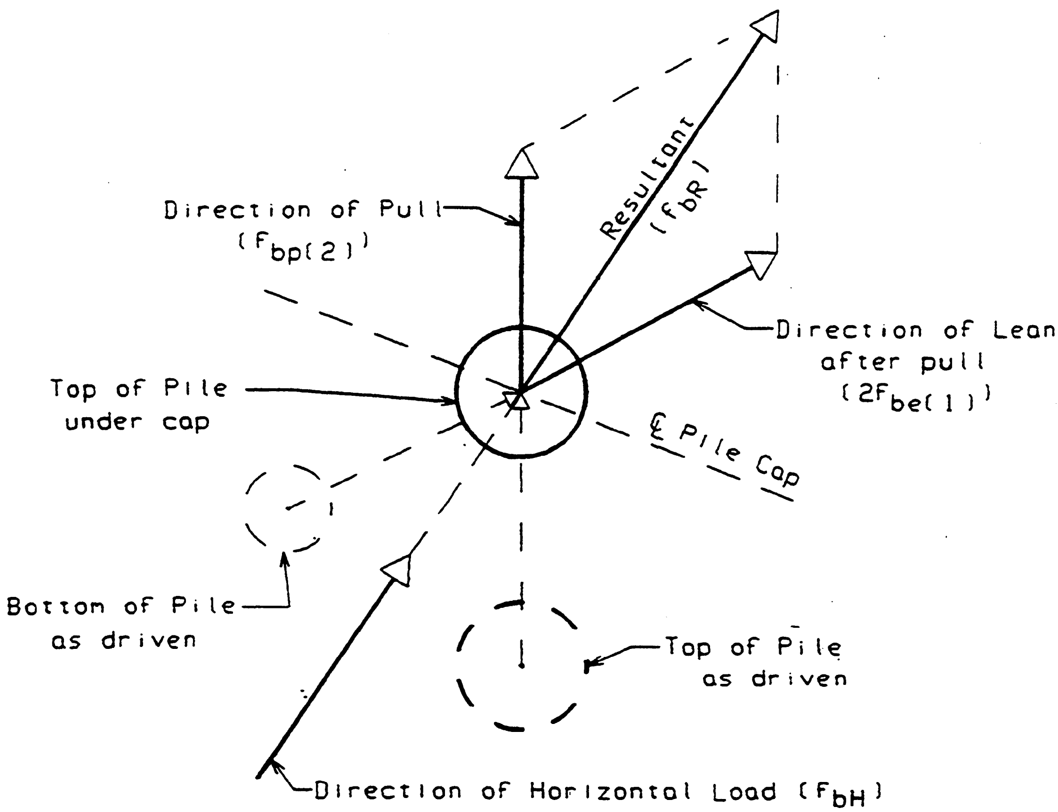


FIGURE 7-19

6 . Plot the stress vectors as shown in Figure 7-19. Note that the vectors are plotted outward from the center of the pile in the direction of pull and lean.

While plotting is not essential to the calculation, it has two important advantages. First, a graphical portrayal of the problem provides a visual check on the direction and magnitude of the resultant. Second, if the vectors are plotted on a large enough scale, the resultant stress value may be scaled with sufficient accuracy to use in the remaining calculations.

7 . Calculate (or scale.) the resultant bending stress.

Axial compression is not affected by the excessive pile pull or pile lean; consequently, it is unnecessary to recalculate the compressive stress.

For a Type I bent, the combined stress expression is:

$$\frac{f_{bR}}{3F_b} + \frac{2f_c}{3F_c} \leq 1.0$$

When the pile to be evaluated is in a Type II or Type III bent, the effect of horizontal deflection must be considered. However, since the bending stress produced by the horizontal load is not affected by excessive pull and/or excessive lean, the bending stress values to be used in the combined stress expression are the values previously calculated for the design review. Also, since the horizontal design load may act in any direction, for the analysis it is assumed to act in the same direction as the resultant force [f_{bR}] because this will produce the highest stress. (See Figure 7016.) Therefore, all bending stresses will be additive.

For a pile in a Type II bent the combined stress expression is:

$$\frac{f_{bR} + 2[f_{bH} + f_{be(2)}]}{3F_b} + \frac{2f_c}{3F_c} \leq 1.0$$

When the pile being evaluated is in a Type III bent, it is a also necessary to consider the P-delta effect, and the combined stress expression becomes:

$$\frac{f_{bR} + 2[f_{bH} + f_{be(3)}]}{3F_b} + \frac{2f_c}{3F_c} \leq 1.0$$

Example Problem 15 illustrates the procedure to be followed when evaluating the actual load-carrying capacity of driven piles in Type II and Type III bents.

7-3.05 Capacity of Steel Piles and Steel Pile Bents

Occasionally, anticipated hard driving or a particular site condition will dictate the use of steel piles for falsework support, Additionally, steel piles may be used where foundation loads are of such high magnitude that timber piles, because of their lower load-carrying capacity, are not feasible.

For analysis, steel piles which are cut off and capped near the ground line may be considered as laterally supported against buckling. Accordingly, the load-carrying capacity of such piles will be equal to the driving resistance determined as provided in Section 7-3.01, Introduction, but not more than the pile can carry when analyzed as a short column.

As a general premise, subsurface conditions that dictate the use of steel piles will not be conducive to the development of a true point of contraflexure in the pile. Accordingly, it is Division of Structures policy to consider the piles in a steel pile bent as columns pinned at the pile tip. For analysis, the tip may be assumed as fixed against lateral translation but free to rotate when subjected to a bending moment.[5]

Depending on the design; some frame stiffness may be developed by the connection at the top of the pile. For example, if the piles are welded to a steel cap, the connection will be fixed; however, the degree of rotational restraint provided by the cap and the extent to which the fixed connection will influence pile stiffness are not readily determined. In view of the indeterminate nature of the problem, the piles should be assumed as pinned at the top, as well as the tip, when making the frame analysis.

The absence of pile fixity will have a significant effect on frame stability, since all horizontal forces must be resisted by the bracing system. Therefore, when investigating the ability of the bracing to prevent frame collapse, the horizontal force produced by vertical load eccentricity (pile lean) must be added to the collapsing force generated by the horizontal design load to obtain the total horizontal force to be resisted by the falsework bracing system.

Depending on their configuration, steel pile bents may provide little or no inherent resistance to overturning. Accordingly, overturning resistance will be an important consideration, since the frame must be stable against overturning as well as stable against collapse. (See Chapter 5 for stability considerations.)

When investigating overturning stability, any theoretical uplift resistance provided by the piles will be neglected.

Evaluating the adequacy of steel pile bents involves the consideration of factors that are not subject to precise analysis; consequently, some subjective judgment is required. In view of this, the falsework drawings should not be approved until the engineer is satisfied that the design assures frame stability under all anticipated loading conditions.

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[5]The procedures used by the Division of Structures for analysis of timber pile bents were developed empirically from an evaluation of the actual load-carrying capacity of timber piles, and thus they are not applicable to steel pile bents.